Tampere University

Sami Martinmäki

A ROBUST COORDINATED VOLTAGE CONTROL IN LOW VOLTAGE NETWORKS VALIDATED THROUGH AN EXPERIMENTAL STUDY

Collaboration of an on-load tap changer and a battery energy storage

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ABSTRACT

Sami Martinmäki: A Robust coordinated voltage control in low voltage networks validated through an experimental study: Collaboration of an on-load tap changer and a battery energy storage
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Currently and in the future, the structure and the control methods of the electricity distribution network are going through changes. The traditional network design principles that have guaranteed sufficient network operation in the past, are not optimal to face the challenges and the possibilities of new technologies. The core principle of electricity distribution has been that electricity is produced in centralized units and then distributed to a customer through a transmission and distribution network. However, with the increase of renewable energy technologies, this distributed generation (DG) has moved part of the generation to the distribution grid.

While thermal constraints can only be coped with reinforcing the network, curtailment or an energy storage, more advanced and cost-efficient solutions are available for the overvoltage problem. To take advantage of these solutions, traditional passive voltage control needs to change towards an active one.

When the DG exceeds the load at a consumer supply point, electricity is transmitted from the customer to the grid, creating a reverse power flow. The reverse power flow can cause the voltage at the customer supply point to rise over the tolerated limits.

This thesis proposes a robust centralised voltage control (CVC) method for low voltage (LV) networks as a solution for the overvoltage problem. The CVC method coordinates operation of an on-load tap changer transformer (OLTC) at a secondary substation and a redox flow battery energy storage (BES) at a customer supply point in a LV network. This method can also be extended with additional components, such an inverters of DG. This thesis compares the CVC method developed in this thesis with other OLTC-based solutions. The compared solutions are a remote measurement based-control method and a fixed set point control method. The comparison is done based on results of the laboratory experiments.

The experiments compared the CVC and the fixed set point control in six different test conditions. The comparison shows that both the CVC and the fixed set point control are able to increase the hosting capacity of a LV network. Both control methods are sufficient in order to neglect negative effect of MV variations, but the CVC is able to manage this with less tap changes. The CVC is able to detect and correct voltage violations that the fixed set point control is not able to.

The comparison between the CVC solely with an OLTC as available component and the CVC with an OLTC and a BES cooperation show that the latter is available to solve wider range of voltage variations.

Keywords: Coordinated voltage control, CVC, On-load tap changer, OLTC, redox flow battery, battery energy storage, BES, fixed set point control, low voltage network, voltage rise

The originality of this thesis has been checked using the Turnitin OriginalityCheck service.

TIIVISTELMÄ

Sami Martinmäki: Keskitetty jännitteensäätö pienjänniteverkoissa. Käämikytkimellä varustetun pienjänniteverkon syöttömuuntajan ja sähköenergiavaraston toiminnan koordinointi.
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Jakeluverkon rakenne ja toimintaperiaatteet ovat käymässä läpi murrosta. Perinteiset sähkön jakeluverkon suunnitteluperiaatteet eivät ota huomioon uusien teknologien tuomia haasteita ja mahdollisuuksia. Perinteisin sähkön jakeluverkon toimintaperiaatteen mukaan sähkö on tuotettu keskitetysti voimalaitoksissa. Sähkön jakeluverkko on toiminut vain sähkön välittäjän asiakkaalle.

Uusiutuvien sähköenergian tuotantoteknologioiden käyttöönotto on kuitenkin siirtänyt osan tuotannosta sähkön jakeluverkkoon.

Mahdolliset termiset rajoitteet voidaan vaativat ratkaistakseen verkon vahvistamista, tuotannon rajoittamista tai energiavarastoja. Jännitteen nousuongelman ratkaisemikseni on olemassa kehittyneempiä ja taloudellisempia ratkaisuja. Näiden käyttöönotto vaatii sähkön jakeluverkon suunnittelu ja toimintaperiaatteiden muuttamista perinteisestä passiivisesta lähtökohdasta aktiiviseen.

Jos hajautettu tuotanto asiakkaan liityntäpisteessä ylittää asiakkaan kuormituksen, ylimääräinen tuotettu teho siirtyy asiakkaalta jakeluverkkoon päin. Tämä aiheuttaa jännitteen nousua asiakkaan liityntäpisteessä, joka voi aiheuttaa laitteiden toimimattomuutta tai hajoamista.

Tässä diplomityössä ratkaisuksi jännitteennousu ongelmalle pienjänniteverkoissa esitettään keskitettyä jännitteensäätöä. Keskitetty jännitteensäätö ohjaa käämikytkimellä varustetun pienjänniteverkon syöttömuuntajan ja asiakkaan liittymispisteessä sijaitsevan energiavaraston toimintaa. Toimintaa voidaan laajentaa myös hajautetun tuotannon ohjaamiseen. Tässä diplomityössä vertaillaan keskitetyn jännitteensäätöä muihin jännitteensäätö ratkaisuihin, jotka perustuvat käämikytkimellä varustettuun pienjänniteverkon syöttömuuntajaan. Vertailtuja ratkaisuja ovat etä- ja paikallismittaukseen perustuvat ohjaustavat. Vertailu tehtiin laboratoriomittauksien perusteella.

Mittaukset vertailivat jännitteensäätötapoja kuudessa eri olosuhteissa. Vertailu osoitti, että kaikki käämikytkimellä varustettuun pienjänniteverkon syöttömuuntajaan perustuvat jännitteensäätötavat lisäsivät pienjänniteverkon kapasiteettiä hajautetulle tuotannolle. Vertaillut jännitteensäätötavat pystyivät poistamaan keskijänniteverkon jännitteenvaihtelun vaikutukset pienjänniteverkon jännitteeseen. Keskitetty jännitteensäätötapa teki tämän muita vähemmillä käämikytkimen asennon muutoksilla. Keskitetty ja etämittauksiin perustuva jännitteensäätötapa pystyvät havaitsemaan jännitteen sallitun jänniterajan ylitykset, joita paikallismittauksiin perustuva jännitteensäätö tapa ei pystynyt.

Keskitetty jännitteensäätötapa pystyy syöttömuuntajan ja energiavaraston koordinoinnilla ratkaisemaan etämittauksiin perustuvaa jännitteensäätöä laajemmat jännitevaihtelut.

Avainsanat: Keskitetty jännitteensäätö, etämittauksiin perustuva jännitteensäätö, paikallismittauksiin perustuva jännitteensäätö, käämikytkin, virtausakku, sähköenergiavarasto, pienjänniteverkko, jännitteen nousu

PREFACE

This Master of Science thesis was written in TU Dortmund University and Tampere University. I would like to give special thanks to The Fortum foundation, The Association of Electrical Engineers in Finland, The Ekosen Orpohuoltosäätiö and The Erasmus for supporting me in my studies.

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Tampere, 8 November 2019

Sami Martinmäki

CONTENTS

LIST OF FIGURES

List of Symbols and abbreviations

DG	Distributed generation
LW	Low voltage
MW	Medium voltage
CVC	Coordinated voltage control
FSC	Fixed set point control
TC	Time based control
AMR	Automated meter reading
LVR	Line voltage regulator
SoC	State of charge

$P_{Tr,ref}$	Maximum power of a network used as a reference
P_{Tr}	Measured power at a secondary substation
V_{ref}	Reference voltage when power is at the maximum power rating
$V_{estimated}$	Estimated voltage set point
V_{Tmax}	Maximum tolerated voltage
V_{Tmin}	Minimum tolerated voltage
V_{Mmax}	Maximum measured voltage
V_{Mmix}	Minimum measured voltage
V_{M1}	Voltage measurement 1
V_{M1}	Voltage measurement 2
V_{M1}	Voltage measurement 3
V_{Mn}	Voltage measurement n´th
mr	Margin
V_{mr}	Voltage value of the margin
V_{Set}	Voltage set point
V_N	Nominal Voltage
V_{SS}	Secondary substations measured voltage
V_{BUS1}	Busbar 1 voltage
V_{BUS2}	Busbar 2 voltage
V_1	Voltage in bus one
V_2	Voltage in bus two
$T1$	Timer for exceeding the tolerated voltage
$T2$	Timer for exceeding the quick return voltage limits
TP	Tap Position
$TP10/0.4kV$	Tap Position of 10/0.4 kV OLTC
$TP10/10kV$	Tap Position of 10/10 kV OLTC
R	Resistance
X	Reactance
P	Active power
Q	Reactive power
P_l	Active power of the load
P_g	Active power of the generation
Q_l	Reactive power of the load
Q_g	Reactive power of the generation

1. INTRODUCTION

Currently and in the future, the structure and the control methods of the electricity distribution network are going through changes. The traditional network design principles that have guaranteed sufficient network operation in the past, are not optimal to face the challenges and the possibilities of new technologies. The core principle of electricity distribution has been that electricity is produced in centralized units and then distributed to a customer through a transmission and a distribution network. This has resulted in a unidirectional power flow, which has allowed distribution network planning being based on the maximum and the minimum load conditions. Network components have been assumed to be passive, meaning that their state does not depend on the state of the network. [1]

In parts of the distribution network these assumptions are not valid anymore. Distributed generation (DG) has moved part of the generation to the distribution grid. Small-scale photovoltaic generators with typically rated power ranging from 1 to 10 kW, are being installed in parallel with domestic consumers in low voltage (LV) networks. Installations of these generators are done via “Fit-and-Inform” policy, which exaggerates the effect [2]. The “Fit-and-Inform” policy means that domestic consumers are allowed to install photovoltaic generators as long as they inform their distribution system operator. Whether the effect of the DG to operation of the network is positive or negative, is depending on the size, type, location and operational principle of the DG [1].

When the DG exceeds the load at a consumer supply point, electricity is transmitted from the customer to the grid, a creating reverse power flow. This results to the distribution network with bidirectional power flow. The reverse power flow can cause the voltage at the customer supply point to rise over the tolerated limits [1]. For example, in a German rural and suburban LV networks the hosting capacity of the DG is restricted due possible over voltages [3]. While the thermal constrictions can only be achieved with reinforcing the network, curtailment or an energy storage, more advanced and cost-efficient solutions are available for this overvoltage problem [3]. To take advantage of these solutions, the operational and the planning principles of the distribution network would need to be changed [1].

Numerous studies have been conducted regarding these solutions for the overvoltage problem. This thesis proposes a robust centralised voltage control (CVC) method for LV networks as a solution for the overvoltage problem. The CVC method coordinates operation of an OLTC at a secondary substation and a redox flow battery energy storage (BES) at a customer supply point in the LV network. This method can also be extended with additional components, such as inverters of DG. This thesis compares the CVC method developed in this thesis with other OLTC-based solutions. The compared solutions are a remote-control method and a fixed set point control method. The comparison is done based on results of the laboratory experiments.

1.1 Motivation

Increase of renewable energies has been a trend in Europe during the past years, with the 20-20-20 goals of the European Union (20% increase in energy efficiency, 20% reduction of CO2 emissions and 20% increase in renewables by 2020). For example from 2000 to 2015 in Germany 21 GW of a photovoltaic generation is installed to LV networks, which majority of it consists of a small-scale rooftop installations [3].

In June 2018 the council, The European parliament and the commission on reached provisional agreement on a new governance system that helps ensure that the EU and the member states reach 2030 goals regarding greenhouse gas emissions reductions, renewables and energy efficiency. This includes the renewable energy directive, which sets a new, binding renewable energy target of 32% of final energy consumption for 2030. [4] This indicates that increase of renewable energy technologies will also be trend in the future. This increase of renewable energies will also mean increase of DG, which will make voltage rise problem to become more relevant.

1.2 Objectives of the thesis

The objective of this thesis is to create a robust CVC method to control voltage in LV networks. This CVC method is compared with two other OLTC-based control methods. The comparison is based on laboratory experiments conducted at Smart Grid laboratory of TU Dortmund University. The goals for this CVC method were that it must be robust and requires only minimal communication within the network.

The voltage of the LV network is controlled by using an OLTC. Control actions are based on data of remote measurements from the strategic points in the network. Measurements could be based on, for example, the automated meter reading (AMR) technology. The strategic points include points with production and points at the end of feeder that has the most significant voltage drop. If the voltage difference between the maximum and the minimum voltage in the network becomes too high, an assist call is sent to the network devices that have the possibility to contribute to the voltage control. The test environment in this thesis includes a BES, which was used for voltage control.

In the second chapter of this thesis the basic principles of voltage control are discussed along with a methods of voltage rise mitigation. In the third chapter the CVC control method is explained, different OLTC-based control methods are compared and the BES voltage control is explained. The fourth chapter introduces the Smart Grid laboratory of TU Dortmund's University and the Node-RED programming tool. The fifth chapter explains the methodology of measurements. In the sixth chapter, the results measurements are shown. The seventh chapter includes discussions and the conclusions are presented in the eight chapter.

2. VOLTAGE CONTROL IN LOW VOLTAGE NETWORKS

The objective of voltage control in the distribution networks is to maintain voltage within the tolerated limits. If the tolerated limits are exceeded, it can resolve in malfunction or breakage of network components or customer devices. These tolerated limits vary in different countries. In Finland and in several other European countries, limits are defined by the European standard EN-50160. [5]

According to the standard, under normal operating conditions, during each period of one week, 95% of the 10-minute mean values of the root-mean-square values of the supply voltage should be within ± 10% range of the nominal voltage. Also, all of the 10-minute mean values of the root-mean-square values of the supply voltage should be within + 10 % and - 15 % of the nominal voltage. For special remote network customers, allowed voltage variations can be extended to + 10 % and - 15 % of the nominal voltage, but the network customers should be informed of the conditions. [5] The standard provides the minimum requirements for the voltage, however the voltage range used in network planning can be narrower [1].

The traditional approach to LV network voltage control is passive. The distribution network is designed to withstand the maximum and the minimum conditions without voltage violations, when the voltage is regulated at a primary substation using an OLTC. The traditional control method used to control voltage at the primary substation is line drop compensation. In this control method, voltage and current are measured at the secondary side of the transformer in primary substation. Measured current is used to estimate load currents. Impedances used in calculation are determined by the desired voltage drop compensation. Estimated load currents and impedances are used to estimate voltage drops. Line drop compensation control method may fail under high penetration on a DG, because the prediction of load currents becomes difficult with intermediate DG in the network. [6] [7]

A simplified schematic of voltage in a network without the DG is presented in Figure 1.

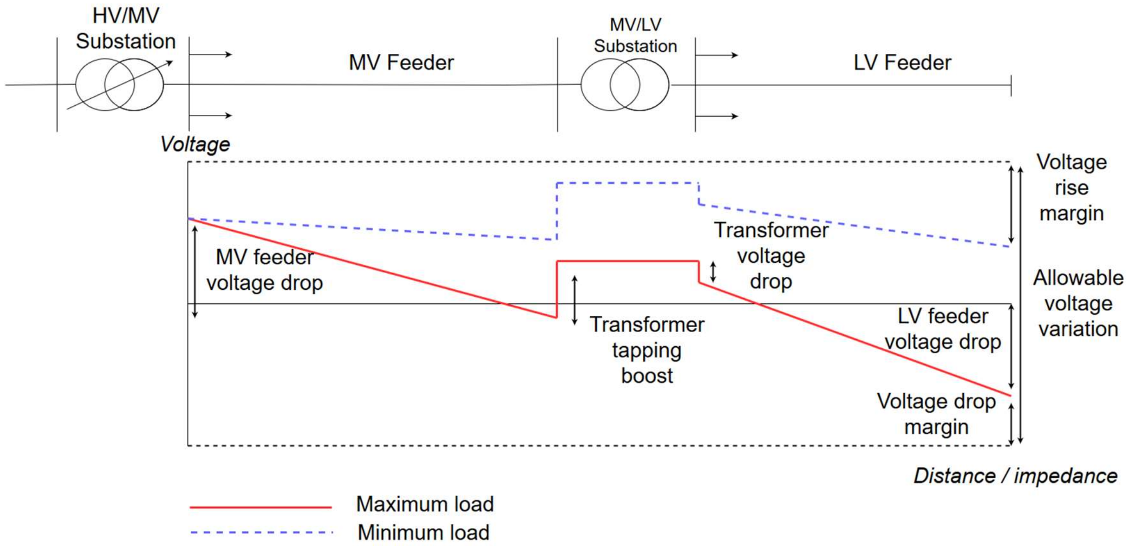

Figure 1. *The voltage variation of the distribution network without the DG, modified from* [1].

In the upper part of Figure 1 structure of the network is presented, with an OLTC at the primary substation and an off-load tap changer transformer at the secondary substation. The voltage level can be adjusted at the primary substation, from where on amplitude of the voltage will decline. The tap ratio of the off-load tap changer transformer is adjusted when it is installed with “fit-and-forget” approach. The network is designed in a way that the standards tolerated ± 10 % voltage variation is divided between the medium voltage (MV) and the LV networks. In Figure 1 the red line describes condition with the maximum load and the dotted blue line condition with the minimum load. In the minimum load condition, the voltage rise margin is seen at the upper right corner of Figure 1. If the DG is connected to the customer supply point, the voltage can rise over the tolerated limits in the condition of the minimum load and high distributed generation. This is shown in Figure 2.

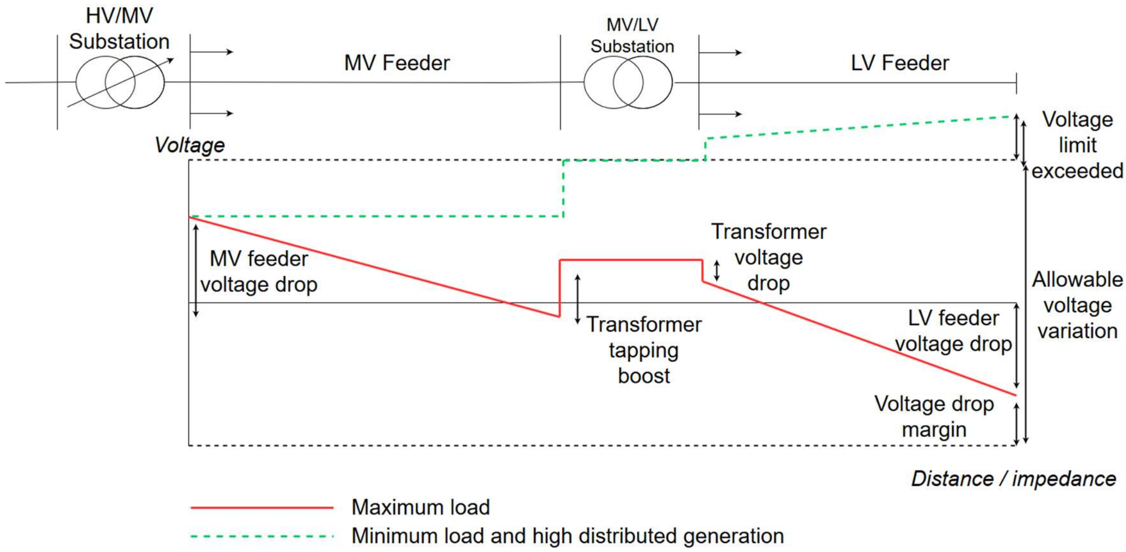

Figure 2. A network with a distributed generation, modified from [1].

The approach of the traditional network planning in situation of Figure 2 would be to increase conductor size in the feeder or size of the supply transformer of the LV network. This would decrease the voltage drop in the LV network. However this approach does not necessarily guarantee the most cost-effective solution. [8]

An option for a passive voltage control approach is an active voltage control. In an active voltage control state of the equipment of the network depends on the state of the network [1]. One active voltage control method for LV networks is to place an OLTC at a secondary substation, which can adjust the voltage at a LV side of the transformer. Overall variety of an alternate solutions for the traditional approach are presented in Chapter 2.2. A more detailed explanation of OLTC-based solutions is presented in Chapter 3.1. Placing an OLTC at the secondary substation would alter the situation in Figure 2 to one presented in Figure 3.

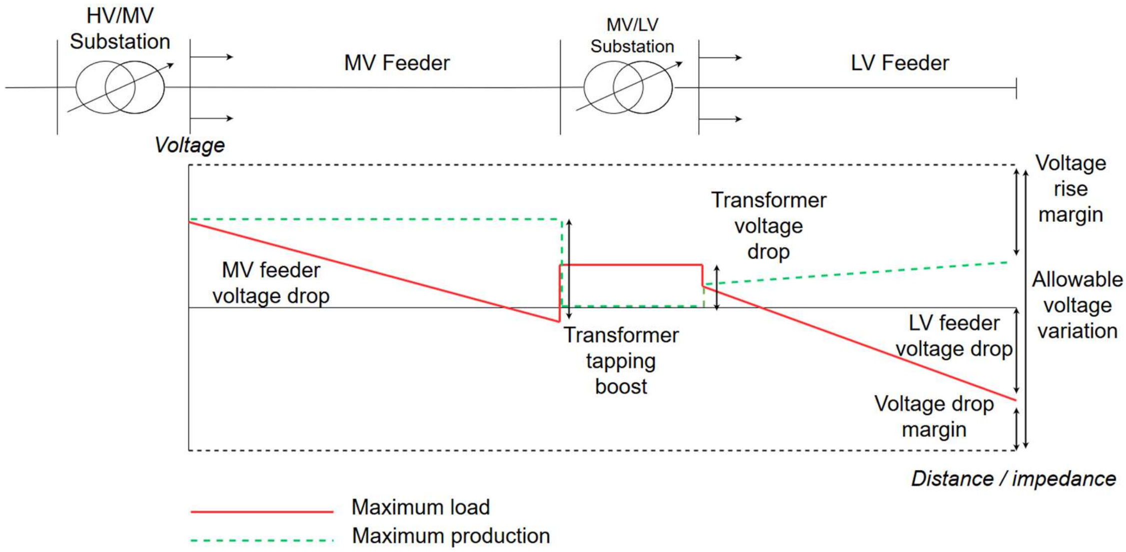

Figure 3. A network with an OLTC at a secondary substation, modified from [1].

Figure 3 illustrates situation, where the OLTC of the LV network is controlled with a fixed set point control. The voltage is measured at a secondary side of the transformer and kept constant by changing tap ratio of the OLTC [9]. In this way, the complete allowed range of ± 10 % of the nominal voltage can be used in the LV network. This approach also neglects the voltage variations from the MV network that would otherwise affect the voltage at the LV network. Figure 4 presents situation, where the load and the generation in the LV network are above the upper voltage limit.

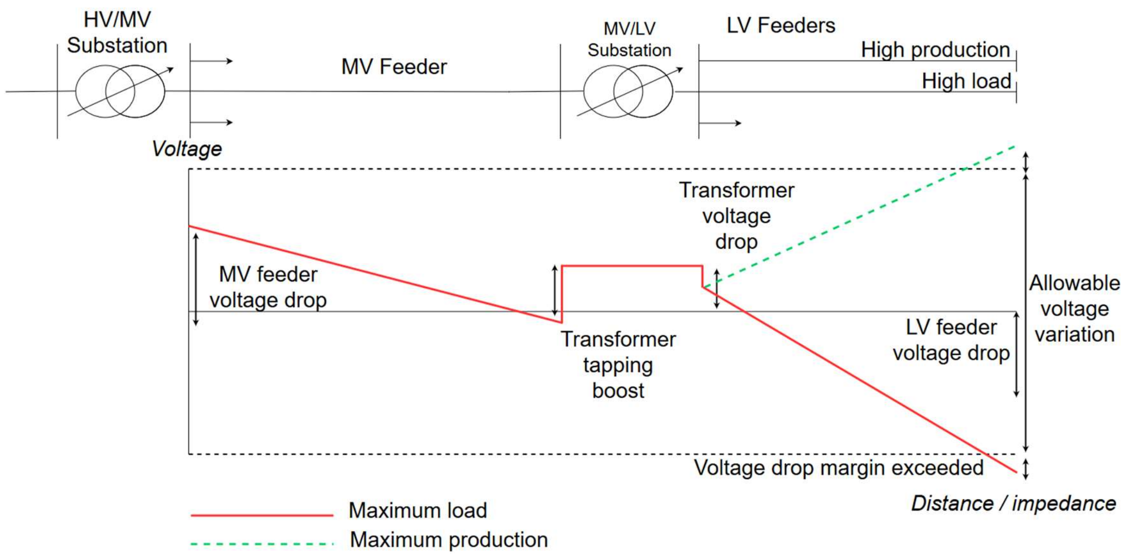

Figure 4. A network with an OLTC at a secondary substation, modified from [1].

If these maximum load and maximum production conditions occur at different times, this problem can be solved with remote monitoring-based control method. The voltage would be measured from points of the production and from point that is the furthest away from the transformer. The remote monitoring-based control method would adjust set point of the OLTC, in order to keep measured voltages within the tolerated limits. [9]

Another possible solution is a time-based control strategy, which would change tap ratio of an OLTC according to the time of day. The maximum DG is around the noon and the peak demand is in the evening. An OLTC would step voltage down in the morning and up in the afternoon. [9]

However, either of these control methods would not be able to solve the voltage problem, if the high load and high generation would occur simultaneously in different feeders and the voltage difference between voltages of the feeders would be higher than the tolerated ± 10% of the nominal voltage. This would cause the control of the OLTC to freeze or to step up or down continuously. This situation can be solved by applying the CVC method developed in this thesis. In the case of simultaneous high load and generation, it would send the help request to other devices that are able to contribute in voltage control.

In this thesis, the LV network has a BES at the customer supply point. After receiving the help request, the BES would charge or discharge depending on where it is located in the network. This would affect the voltage at the feeder where the BES is connected. If the effect was enough to decrease the voltage difference between the maximum and the minimum measured voltage to the tolerated limits, the OLTC could do step change to the proper direction.

In this chapter the voltage drop and rise effect are explained and different ways to mitigate voltage drop are discussed.

2.1 Voltage rise and drop effect

Power flows in a distribution network are altered by a DG, which affects voltage directly. A DG can also affect the voltage by affecting an existing voltage control equipment [1]. Because installation of a DG can cause voltage rise near the generation, this voltage rise can become a limiting factor for the hosting capacity of the LV network for the DG [10]. The effect to voltage caused by the DG depends on its real and reactive power output. Voltage rise or drop effect can be examined in a two-bus system. [1] This is illustrated in Figure 5.

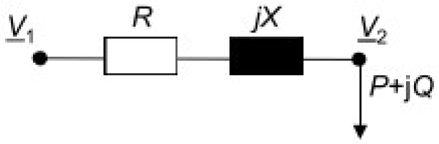

Figure 5. Simplified model of line section [1].

In Figure 5, $\underline{V_1}$ and $\underline{V_2}$ present voltages of the bus one and the bus two. *R* and *X* present the resistance and the reactance of the feeder. *P* and Q present the real and the reactive powers absorbed by the bus two. [1] The voltage in the bus two is presented in Equation (1),

$$\underline{V_2} = \underline{V_1} - (R + jX)\frac{(P - jQ)}{\underline{V_2^*}} \tag{1}$$

in which $P = P_L - P_G$ and $Q = Q_L \pm Q_g$. With $+Q_g$ the DG consumes reactive power and with $-Q_g$ DG generates reactive power to the network [11]. If the angle of the voltage at the bus two is set to zero $\underline{V_2} = V_2\angle 0$, voltage difference between the bus one and two ΔV becomes following.

$$\Delta V = \underline{V_1} - \underline{V_2} = \frac{(RP + XQ)}{V_2} + j\frac{(XP + RQ)}{V_2} \tag{2}$$

Phasor diagrams for the voltages in two bus system are presented in Figure 6.

Figure 6. Phasor diagrams of voltage in the two-bus system [1].

The phasor diagram **a** in Figure 6 represent voltage of the load bus and the phasor diagram **b** represent the voltage of the bus with production. The phasor diagram makes the assumption that the real power is significantly larger than the reactive power. Therefore $|RP| > |XQ|$ and $|XP| > |RQ|$. If the voltages are assumed to be near their nominal value and the angle between voltage phasors is small, then voltage drop in Equation ((2)) can be approximated to Equation (3). [1]

$$\Delta V = \frac{RP + XQ}{V_2} \tag{3}$$

Equation (3) indicates that a load always causes a voltage drop. This is why conventional distribution systems voltage profile is decreasing towards the end [12].

Depending on the real and the reactive power consumption of a load, the real and the reactive power production of a DG, and the reactance per resistance (X/R) ratio of a line, Equation (3) concludes that a DG can either decrease but also increase voltage along a feeder. If the active power output of a DG is higher than the load in that point of the network, it causes voltage increase at V_2. V_2 can rise over V_1 and conclude to rising voltage profile towards the end of the feeder. [11]

2.2 Voltage rise mitigation

In weak distribution networks, a DG can cause voltage rise that can become the limiting factor for the hosting capacity for a DG. There are several different approaches to mitigate voltage rise. The voltage can be adjusted at a primary or a secondary substation or at some point along a feeder. Impedance of the feeder can be decreased by increasing the size of the cable. The real and the reactive power flows of a network can be controlled by controlling the real and the reactive powers of a DG. Next in this chapter different methods are listed, from which one or a combination can be used to decrease the maximum voltage at a customer supply point. [1]

- Decrease the impedance of the feeder by increasing the size of the conductor [1]
- Adjusting voltage of a LV network by changing off-circuit taps of a MV/LV transformer [1]
- Adjusting voltage of a LV network by changing tap ratio of an OLTC at a primary substation [1]
- Adjusting voltage of a LV network by changing the tap ratio of an OLTC at a secondary substation[13] [3]
- Adjusting voltage of a LV network by installing a line voltage regulator on a feeder [1] [14] [3]
- Allowing active and reactive power control of a DG [1] [3]
- Installing or using existing battery energy storage in a LV network for voltage control [1] [15]
- Placing active or passive reactive power compensators on a feeder [1]
- Adjusting loads in a network in order to control voltage [1]

At the moment voltage rise mitigation is commonly carried out in a passive way, which means increasing the size of a conductor [1]. One active way to control voltage directly is to use an OLTC at a primary or a secondary substation. However, traditionally only primary substations are equipped with an OLTC. Secondary substations are equipped with off-load tap changers. In order to change tap ratio, an interruption in the power supply is required. This tap ratio is fixed, which means that the suitable tap position for all load situations is needed to be found. Further discussion about OLTC-based control methods can be found in Chapter 3.1. [1]

Another way to adjust the voltage directly is to use a line voltage regulator (LVR). The LVR is installed to one feeder and it is able to adjust voltage in that feeder. After the installation, the LVR can adjust the voltage without interruptions. [14]

A different kind of approach than direct voltage control is reactive and active power management. This can be performed by controlling the real and the reactive power of a DG or a BES. One other way to control active power in network is to use demand response. The customer supply point voltage can be reduced by controlling the amount of the real and the reactive power flowing in the network. This can be done by either increasing the consumption or decreasing generation of real or reactive power. A DG and a BES can have ability to control both real and reactive power. [1] In practice active power based voltage control using a BES would mean that excess DG is charged into batteries during the peak hours of production and discharged to the grid during the peak hours of demand [15]. The DSO doesn’t have ownership of DG, BES or loads, so the active power control could have to happen in two ways. In market driven way or according to agreement between the DSO and the owner of BES, DG or loads. This would leave BES open for other use cases, for example frequency control or storage for unused DG. For this reason, it is more efficient to first use available reactive power reserve of DG or BES. [7]

Reactive power management of a DG can be done using several different control methods. One approach is to have constant cos(φ) for all of the DG. This is a simple control method to be implement. Before August 2011, there were no regulation in Germany regarding reactive power management in LV networks, so all photovoltaic (PV) systems before this date were generally built with fixed cos(φ) of 1. After this, the VDE (German electrical association) has recommended guideline that defines a standard cos(φ) for the DG. In this guideline cos(φ) depends on power related to the maximum power. [3]

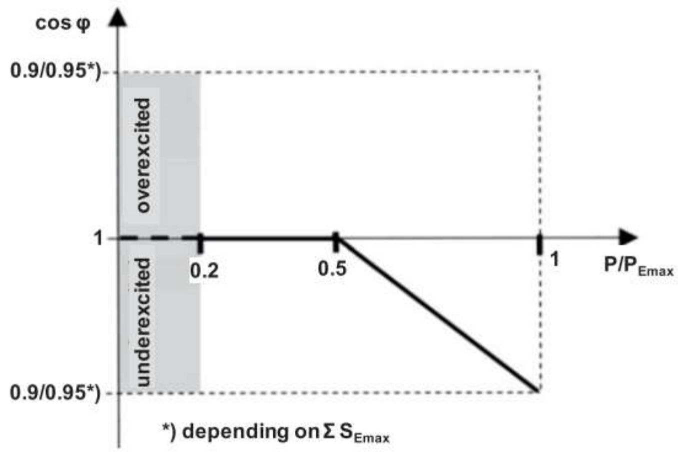

Figure 7. Characteristic of the cos(φ) curve for a distributed generation in LV networks [3].

The guideline curve for cos(φ) depends on apparent power of a PV system. cos(φ)=0.95 for systems up to 13.8 kVA and cos(φ)=0.9 for larger ones. Another approach for the reactive power control is to regulate the reactive power according to the voltage at a customer supply point, which is shown in Figure 8. [3]

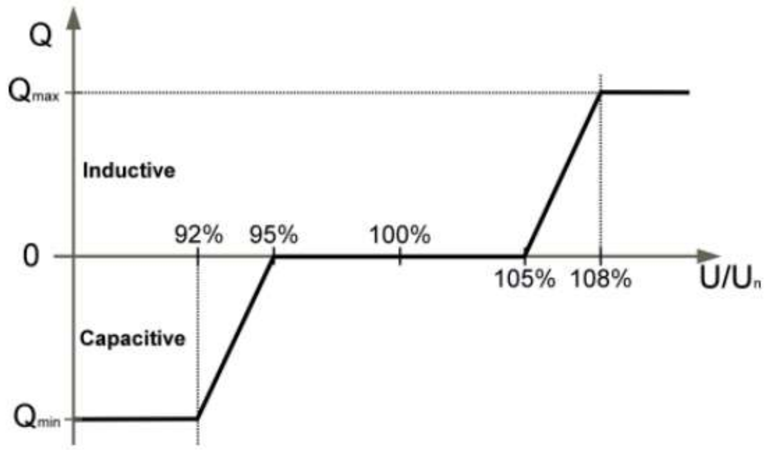

Figure 8. Reactive power regulation according to voltage at connection point [3]

As seen in Figure 8, under excited operation of a DG inverter would start from 105%, which would result in voltage reduction. Control characteristic also have 2% margin. [3] One direct way to influence reactive power is the use of reactive power compensators, which are used in MV networks. [1]

When there is significant voltage rise due a DG, due the low X/R ratio of cables in LV networks, the reactive power voltage control method is not sufficient to maintain voltage within the tolerated limits [16] [8]. Because of the low X/R ratio of cables in LV networks, the effect of reactive power voltage control of DG to voltage of a LV network comes mainly from reactance of a supply transformer at a secondary substation and cables of a MV network. [7] Therefore, it mainly affects voltage at secondary side of a supply transformer of a LV network, not along the feeders of a LV network.

As a conclusion for voltage rise mitigation in LV networks, there are currently two practical solutions for a distribution network operation to solve the overvoltage problem. First one of these is the solution of the traditional grid planning method, increasing conductor size. Other practical solutions are an OLTC at a secondary substation-based solutions. [8]

3. COORDINATED VOLTAGE CONTROL

A coordinated voltage control is a method that determines its control actions based on measurements at several locations in a network. The advantage of this method is that it can greatly increase the hosting capacity of a LV network. The disadvantage of the CVC is that it requires data transfer between network components [1]. In this chapter, firstly different kind of OLTC-based control methods are discussed. After this the CVC and the BES control methods are explained.

3.1 Comparison of different OLTC-based control methods

An OLTC is a device that can mechanically alter its winding ratio in discrete steps, while the transformer is energized. Step changes of an OLTC are controlled manually or by using an automatic voltage regulator (AVR) relay. [1]

The basic OLTC control concept is that the controlled voltage V_{ss} is kept between tolerated bandwidth between V_{Tmax} and V_{Tmin} [9]. This is shown in Equation (4).

$$V_{Tmax} > V_{SS} > V_{Tmin} \tag{4}$$

Voltage is maintained between the tolerated bandwidth by changing the tap ratio of a transformer. The tolerated bandwidth depends on the situation, however the bandwidth is required to be wider than the effect of one tap change to the voltage. The voltage is checked frequently, but a change in the step position is executed only if the voltage has exceeded the tolerated voltage value for predefined time *T1*. This is illustrated in Figure 9.

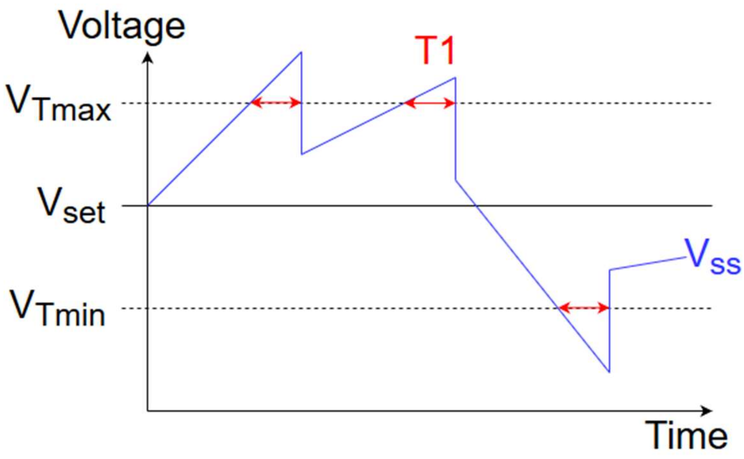

Figure 9. Basic concept of OLTC voltage control, modified from [3].

The basic control method of an OLTC is the fixed set point control (FSC), in which controlled voltage is measured at the secondary side of a transformer. Tolerated bandwidth of the FSC is kept constant [9]. For example, if set point would be 230V, the tolerated voltages could be +/- 2% the set point.

Extension of this basic control method is to adjust the set point voltage based on different measurements. An example of this is the power dependent set point voltage method. In this method the voltage and the power are measured at the secondary side of a transformer. Voltage set point is adjusted according to power. This is illustrated in Equation (5),

$$V_{estimated} = V_{SS} + V_{ref} \cdot \frac{P_{Tr}}{P_{Tr,ref}} \tag{5}$$

in which $V_{estimated}$ is estimated voltage set point, V_{SS} is measured voltage, V_{ref} reference voltage when power is at maximum power, P_{Tr} is measured power and $P_{Tr,ref}$ is maximum power of a network.[3]

Other example of a control method where the set point is adjusted according to a measurement is a solar dependent set point voltage control method, which has a similar principle to the power dependent set point voltage control method. In this, the solar radiation is measured at the secondary substation and the voltage set point is adjusted in same principle as in Equation (5), but based on solar radiation. [3]

Other principle than adjusting the set point according to a measurement is to change the voltage set point according to the time. Example of this is time-based control strategy (TC). In order to cause voltage rise, a DG has to coincide with the minimum demand. The peak demand time can vary depending on the country. For example, in the United

Kingdom, the maximum peak hours of demand are at 17:00 – 20:00, which does not coincide with the maximum production of a DG. Therefore, the set point of an OLTC can be modified based on the time of the day. During the moments of high DG and low demand, step position would be set lower than in the evening during high demand and low DG. [9]

Quality of the time-based control method is determined by how predictable generation and demand are. Especially correlation between these two is important. For single test case this information can be available and time-based control method can be viable, but an electric grid designer would not normally have information about this correlation at LV level. The designer would have rely on assumptions about the correlation. Unreliability of the time-based control increases when it is applied to networks with electric heating and cooling, because the maximum demand can be dependent on the temperature, not the clock. In conclusion, even though time-based control method is very robust, proper execution of this control method would be challenging, because control parameters would rely too much on assumptions. [7]

Benefit of these approaches is that they do not require measurement data from elsewhere of a network. Therefore, no data communication infrastructure is needed. However, acquiring measurement data from a network resolve in more accurate behaviour of an OLTC. An example of a control method including a communication infrastructure is a remote monitoring-based control method [9]. Part of this communication infrastructure can utilize the AMR technology [3]. In this control method, measurements are taken from several points of a network and operations of an OLTC are based on these measurements. Measurements can be taken from end points of the feeders or from multiple points along the feeders.

The fixed set point, the remote monitoring-based and the time-based control methods were evaluated by applying these control strategies to real LV network of United Kingdoms. The outcome is that the remote monitoring-based control method can significantly increase the hosting capacity of a LV network for a DG, while limiting tap operations and voltage issues. The time-based control strategy resulted in a comparable performance in terms of voltage issues but resulted in more tap operations. The benefit of this approach is the absence of need for a data communication infrastructure [9].

It is likely that a DSO will choose only one control method for all of OLTCs at secondary substations. Having multiple different control methods could increase difficulty to solve fault situations. [7]

3.2 Coordinated voltage control method

The CVC method can be seen as an extension of the remote monitoring-based control method. In addition to this, the CVC introduces a possibility to control other devices besides an OLTC. The CVC method of this thesis has voltage measurement from strategic points of a network. The Strategic points in this case are points with a production and furthest load from the secondary substation. Logic of the CVC algorithm developed in this thesis is presented in Figure 10.

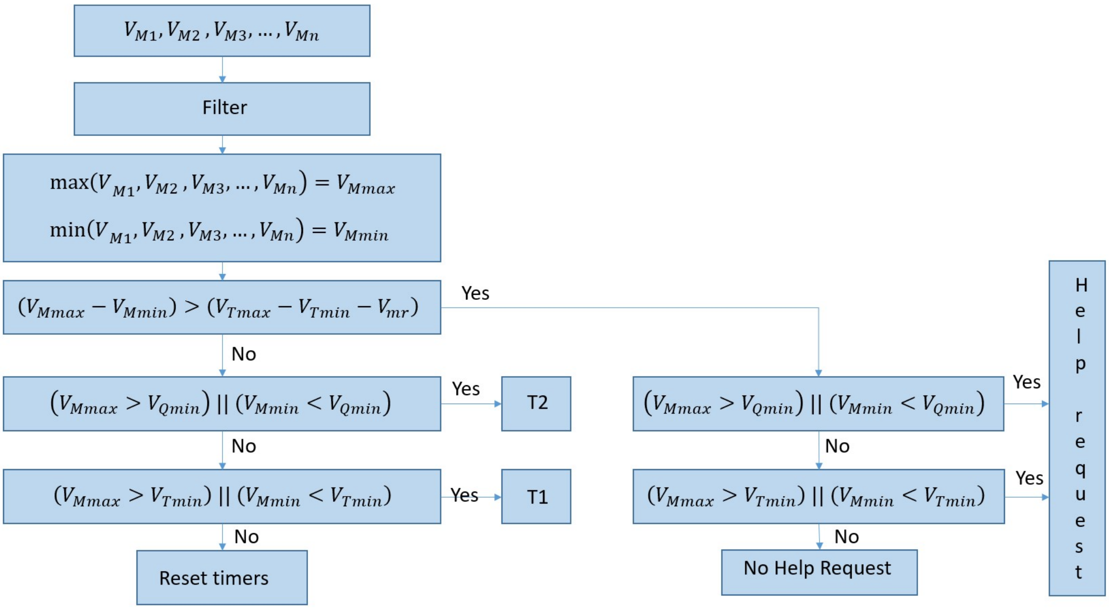

Figure 10. The coordinated voltage control algorithm

The control algorithm receives the voltage measurements V_{M1}, V_{M1}, V_{M1}, …,V_{Mn} from a network. From those the CVC calculates the maximum voltage V_{Mmax} and the minimum voltage V_{Mmin} voltages. This is shown in Equations (6) and (7).

$$\max(V_{M1}, V_{M2}, V_{M3}, \dots, V_{Mn}) = V_{Mmax} \tag{6}$$

$$\min(V_{M1}, V_{M2}, V_{M3}, \dots, V_{Mn}) = V_{Mmin} \tag{7}$$

By changing tap position of an OLTC, the CVC maintains the maximum and minimum voltages between the tolerated V_{Tmax} and V_{Tmin} voltages. This is illustrated in Equation (8).

$$(V_{Mmax} > V_{Tmax}) \,||\, (V_{Tmin} > V_{Mmin}) \tag{8}$$

If the voltage difference between the maximum and the minimum measured values is higher than the voltage difference between the tolerated maximum and minimum values, an OLTC does not change the tap position. This is illustrated in Equation (9).

$$(V_{Mmax} - V_{Mmin}) > (V_{Tmax} - V_{Tmin}) \tag{9}$$

The reason for this is that the voltage limits would not be within tolerance in any possible step position. An OLTC is a discrete component and the CVC could run into situation, where the control algorithm executes continuously tap changes without reaching the steady position [1]. This can happen in situation when the voltage difference between the maximum and the minimum measured values is close but not over the voltage difference between the tolerated maximum and minimum values, which are presented in Equation (10).

$$V_{Mmax} - V_{Mmin} \approx \; V_{Tmax} - V_{Tmin} \tag{10}$$

In this case, if $V_{Mmax} > V_{Tmax}$ or $V_{Mmin} < V_{Tmin}$, step position change can lead to continuous tap change operations. In order to prevent such behaviour, the CVC has margin parameter *mr*. The margin value is given in percentages, from which together with voltage set point V_{set} margin is calculated in voltages V_{mr}. This is illustrated in Equation (11).

$$V_{set} \cdot \frac{mr}{100\%} = V_{mr} \tag{11}$$

The tolerated voltage difference in Equation (9) is decreased by a V_{mr}.

$$(V_{Mmax} - V_{Mmin}) > (V_{Tmax} - V_{Tmin} - V_{mr}) \tag{12}$$

Whether if an OLTC does tap position changes, is determined by Equation (12). If an OLTC cannot change tap positions, it initiates a help request to other devices in a network that are also able to control voltage. However, need for voltage control of an additional devices is tested with same conditions used to test need for step changes. In this thesis, a test case with a redox flow battery (BES) is considered. The voltage control of BES is discussed in Chapter 3.4.

The CVC has two voltage thresholds. The tolerated voltage threshold and the quick return voltage threshold. Exceeding of the tolerated voltage threshold initiates timer T1 and exceeding the quick return voltage threshold initiates timer T2, in which T1 > T2. In conclusion, if $V_{Mmax} > V_{Tmax}$ or $V_{Mmin} < V_{Tmin}$, and condition of Equation (12) is not exceeded, OLTC initiates timer T1 for step position change to a convenient direction. If either V_{Mmax}

> V_{Qmax} or $V_{Mmin} < V_{Qmin}$, the CVC initiates a timer *T2* for quicker step position change to a convenient direction.

Appropriate value of the margin and timers depends of a network and the transformer type. The effect of margin needs to be less than the effect of one tap change anywhere in the network. An OLTC used in thesis has an internal limit of 3 seconds between the tap changes, so 3 seconds is used as a timer *T2*. Timer *T1* was set to 10 seconds.

In case of communication error or fault in grid, the CVC algorithm has a deadband filter. Measured voltages in Equations (6) and (7) are filtered with the deadband filter, so possible faulty measurement is not taken into account in control. However, possible missing measurement of most significant measurement point, exposes algorithm to faulty actions.

3.3 Redox flow energy storage

An energy storage used in this thesis is a redox flow battery. A redox flow battery is an electrochemical system that can controllably and repeatedly convert and store electrical energy to chemical energy and vice versa. [17] The working principle of a redox flow battery is illustrated in Figure 11.

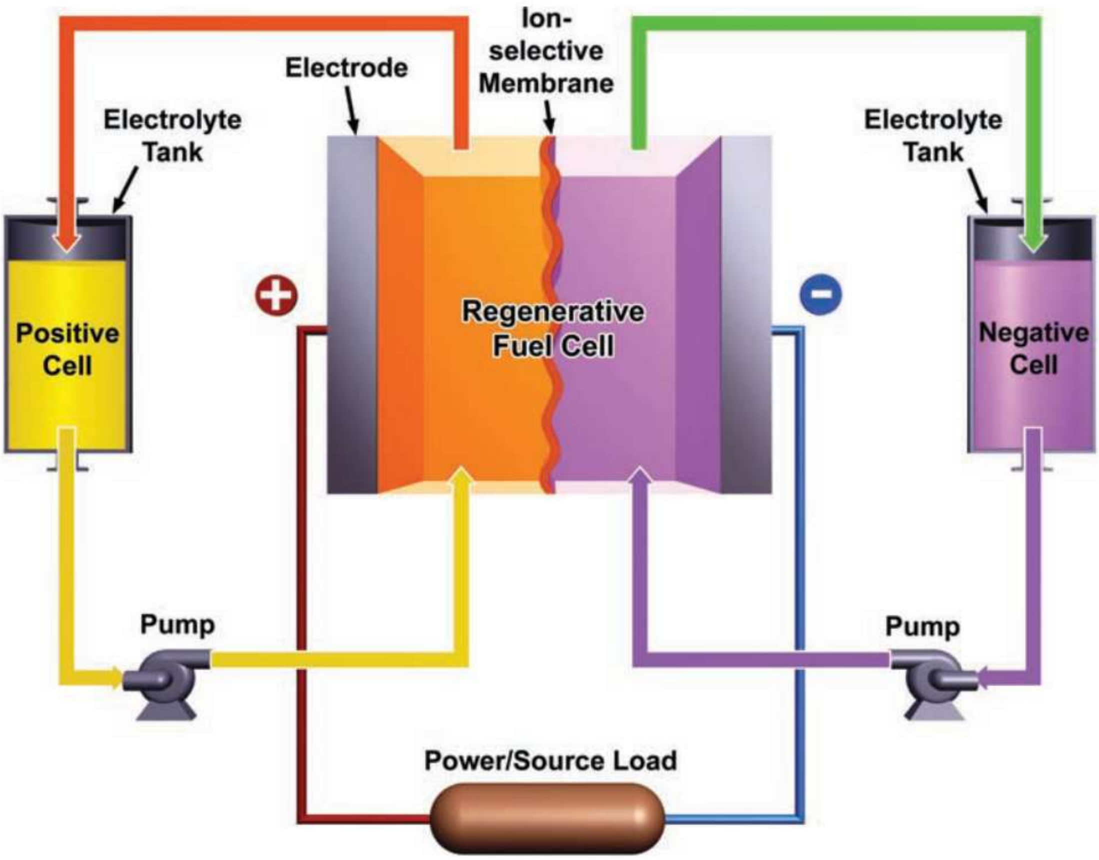

Figure 11. A schematic illustration of the structure of a redox flow battery. [17]

A redox flow battery cell consists of two electrodes and two electrolyte systems. These circulating liquid electrolytes are positive and negative electrolyte. The electrolytes are separated by an ion-exchange membrane or a separator. The energy conversion from electrical energy to chemical potential and vice versa occurs instantly after the electrolytes are flowing through the cell. The main benefit of a redox flow battery along with its high efficiency, short response time, low self-discharge and long life time is its independently tuneable power and storage capacity, which makes it highly scalable. [15]

In comparison to widely used lithium-ion batteries, Redox flow batteries allow more charging cycles but also have lower energy density. Lower energy density makes redox flow batteries less desirable to mobile applications. However, a high number of charging cycles makes it suitable for stationary systems, where energy density is not as relevant factor as in mobile applications. [18] In this thesis the considered BES is a stationary application of redox flow battery.

3.4 Part of the voltage control regarding the battery energy storage

Part of the logic of the coordinated voltage control presented in Chapter 3.2 would locate at the BES. This logic would wait for the help request show in Figure 10 that would initiate the voltage control of the BES. Part of the logic located at the BES is illustrated in Figure 12.

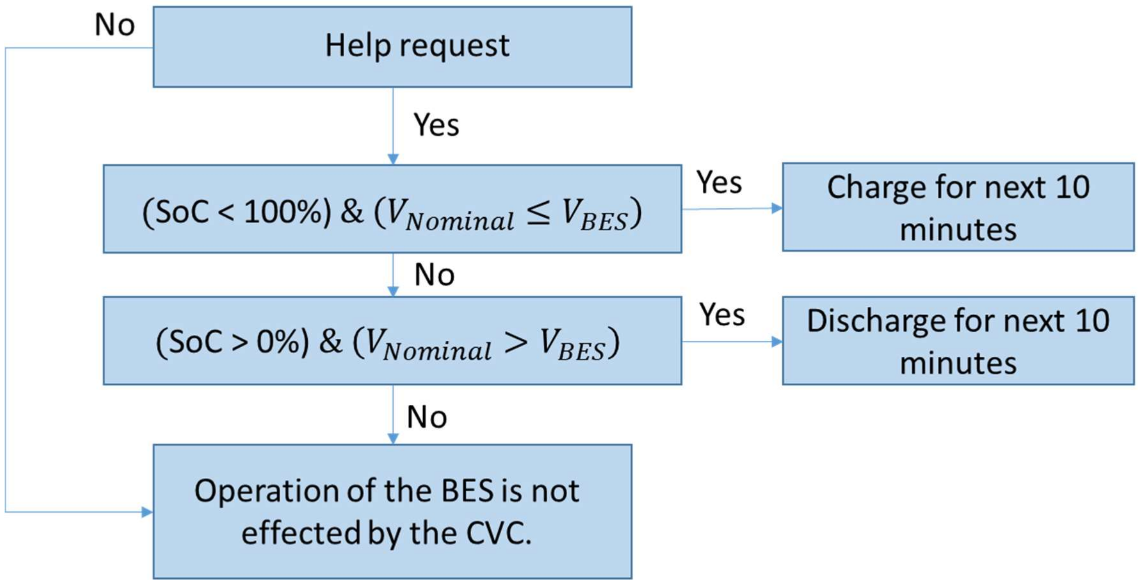

Figure 12. Voltage control logic at a battery energy storage.

The logic at the BES would wait for help request sent from centralized logic of the coordinated voltage control. In practice this could mean, that the CVC could remotely control a relay of smart meter. State of this relay would be indicator, whether help request is on or not. The BES would read the state of this relay. After initiating the voltage control the logic checks if a state of charge (SoC) of the BES is not full and if a voltage measured at a connection point of the BES is higher than the nominal voltage. This is illustrated in Equation (13).

$$(SoC < 100\%)\ \&\ (V_{Nominal} \leq V_{BES}) \tag{13}$$

If the condition in Equation (13) is true, the logic will initiate charge of the BES for next 10 minutes. If the condition in Equation (13) is not true, the logic will check if the SoC of the BES is not 0% and if a voltage measured at a connection point of the BES is lower than the nominal voltage. This is illustrated in Equation (14).

$$(SoC > 0\%)\ \&\ (V_{Nominal} > V_{BES}) \tag{14}$$

If the condition in Equation (14) is true, the logic will initiate discharge for next 10 minutes. If neither of conditions in Equations (13) and (14) are not true, the operation of the BES is not affected by the coordinated voltage control algorithm.

The time of both control actions depends on the expected time of extreme load conditions of a network. 10-minute value for the time of control actions in Figure 12 is set as an example. Value 10-minute is chosen, because the European standard EN-50160 requires 95% of the 10-minute mean values of the root-mean-square values of the supply voltage to be within ± 10% range of the nominal voltage [5]. In case of 10-minute value for the time of control actions algorithm checks every 10 minutes, if contribution of the BES is still necessary.

If the time of control actions would be longer, the possibility of unnecessary contribution of the BES would increase. If the time of control actions would be shorter, possibility of unnecessary on and off switching of the voltage control of the BES would increase, therefore increasing short term exceeding of ± 10% range of the nominal voltage. This would happen, because every time the necessity of the contribution of the BES is checked, exceeding of tolerated voltage values is required (Figure 10), in order to send help request to the BES and trigger voltage control of the BES (Figure 12).

4. SMART GRID LABORATORY AT TU DORTMUND UNIVERSITY

Institute of Energy Systems, Energy Efficiency and Energy Economics (ie3) at TU Dortmund University has Smart Grid Technology Lab with some of the latest technology in regards of low voltage networks and electric mobility [19]. A picture of the laboratory is presented in Figure 13.

Figure 13. Smart grid laboratory

Lot of research related to electric vehicles is done in the lab, but they are not involved in this thesis. A possible schematic of connection using the equipment of the laboratory is presented in Figure 14.

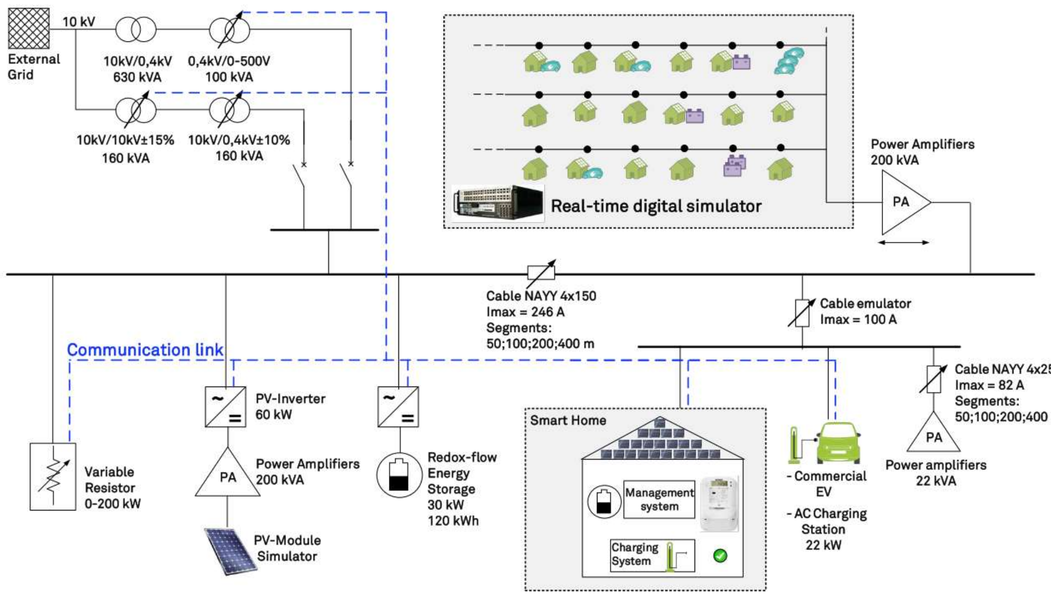

Figure 14. A general layout of one of the possible network configurations at the laboratory [19]

In this picture PA = Power Amplifier, PV = photovoltaic and EV = Electric Vehicle. From components of the picture 10/10 kV OLTC, 10/0.4 kV OLTC, 200 kVA power amplifiers, 0 – 200 kW variable resistor, a cable emulator and a redox-flow energy storage are used in this thesis.

4.1 On-load tap changer

Laboratory has 10/10 kV and 10/0.4 kV OLTC. The type plate values of transformers are presented in Table 1 and Table 2.

10/10 kV OLTC transformer			Rated primary voltage	
Type: 630/12/10 10 0,410 K-PB OLTC			tap position	Primary voltage (V)
Rated Power	630	kVA	1	11000
Connection	Dyn5		2	10750
Short-circuit impedance	4.21	%	3	10500
No-Load losses	736	W	4	10250
Load losses	5950	W	5	10000
Rated primary current	36	A	6	9750
Rated secondary voltage	10000	V	7	9500
Rated secondary current	36	A		

Table 1. *Values of 10/10 kV OLTC transformer type plate*

10/0.4 kV OLTC transformer			Rated primary voltage	
Type: 630/12/10 10 0,410 K-PB OLTC			tap position	Primary voltage
Rated Power	630	kVA	1	11000
Connection	Dyn5		2	10750
Short-circuit impedance	4.34	%	3	10500
No-Load losses	669	W	4	10250
Load losses	5666	W	5	10000
Rated primary current	36.37	A	6	9750
Rated secondary voltage	400	V	7	9250
Rated secondary current	909	A	8	9000

Table 2. *Values of 10/0.4 kV OLTC transformer type plate*

From above we can see that transformers are almost identical, except for the secondary voltage. Table 1 and Table 2 are divided in two sections. The rated values are presented in left side of the table. Voltage of the primary side is presented on the right side of the table. Voltage of the primary side varies. In order to keep the voltage of the secondary side constant, the tap position is changed.

OTLCs can operate in several different methods. The operation method is defined by the connection cabinet outside the bunker of transformers.

Figure 15. Selection of OLTC operation

Step positions of an OLTC can be controlled manually locally or remotely. Step position can be given remotely in two ways. The first way is using a program provided by the supplier of the OLTC. The second way is to write step position using Modbus communication. Instead of giving manually step position, user can alternatively give voltage set point. The OLTC then uses its own control logic, which measures voltage from secondary side of the transformers and tries to keep it within the acceptable limits. The supplier of the OLTC has provided a program to control logics of the OLTC.

The control algorithm of the program provided by the supplier of the OLTC requires five control parameters. Regulation time, tolerance, quick return, undervoltage block and overvoltage block. Tolerance is given in %, from which tolerance+ and – values are calculated. If measured voltage exceeds these limits, program waits regulation time and then operates tap position change.

Program also has a quick return parameter, which is given in percentages, from which program calculates quick return+ and – values. If these values are exceeded, step position will change in 3 seconds. The program has under and overvoltage block values that are meant to prevent from taking measurements of fault situations into account. If the voltage set point exceeds these values, the control algorithm does not operate until measured voltage is back within tolerated limits. The measured voltage value is average of three phases.

4.2 Redox-flow energy storage and power amplifiers

Laboratory has vanadium redox flow energy storage with power of 30 kW and capacity of 120 kWh. Redox flow energy storage is presented in Figure 16.

Figure 16. Redox-flow energy storage[19]

The redox flow energy storage is controlled by giving set point for active power, which can be ± 30 kW or something in between. Feature to also control reactive power was under implementation. This feature would allow reactive power control of the BES. From perspective of voltage control, there is no other option but to give command as a set point for active power. Laboratory has two 0 to 105 kVA three-phase system power amplifiers, which are presented in Figure 17.

Figure 17. Power amplifiers [19]

Power amplifiers are custom P-HIL (power hardware in the loop) solution from company EGSTON. Power amplifiers can operate as DC and AC in both as load or generation. Power amplifiers can be controlled remotely using separate program.

4.3 Variable resistor and network emulator

Laboratory has a 200 kW 3-phase variable resistor, which is presented in Figure 18.

Figure 18. Resistor

Resistor has a discrete resistance adjustment. It consists of smaller resistors, which can be turned on and off using switch seen in the picture. Because resistance is set to fixed value, when voltage changes, also the power value of resistor changes. Unlike power amplifiers, resistors power is dependent on voltage.

There are two different cable emulators in the laboratory, which are presented in the Figure 19.

Figure 19. Cable emulators

Cables are installed to the ground underneath the laboratory. Both ends of the cables are brought to the connection points, which can be seen in upper part of the cabinet. On bottom part, there are connection points to Cab7 and Cab8 as well as a busbar system for more complex network topologies. A desired setup is made using small interconnection cables. One cabinet has NAYY4x25 cables and other has NAYY4x150 cables. Both have 50m, 100m, 200m, and 400m segments of cables.

4.4 Measurement devices and connection cabinets

The OLTC, BES, resistor and network emulator are connected in connection cabinets. There are two connection cabinets 7 and 8 in the laboratory, which are presented in Figure 20.

Figure 20. Connection cabinets 7 and 8

In upper part of each cabinet there is busbar system, which is divided in two sections. Between these sections there is current measurement. This way current can be measured from desired point of the network topology. In middle and bottom part of cabinets there are connection points to other devices of the laboratory. Cabinets are equipped with Kocos measurement devices, which is presented in Figure 21.

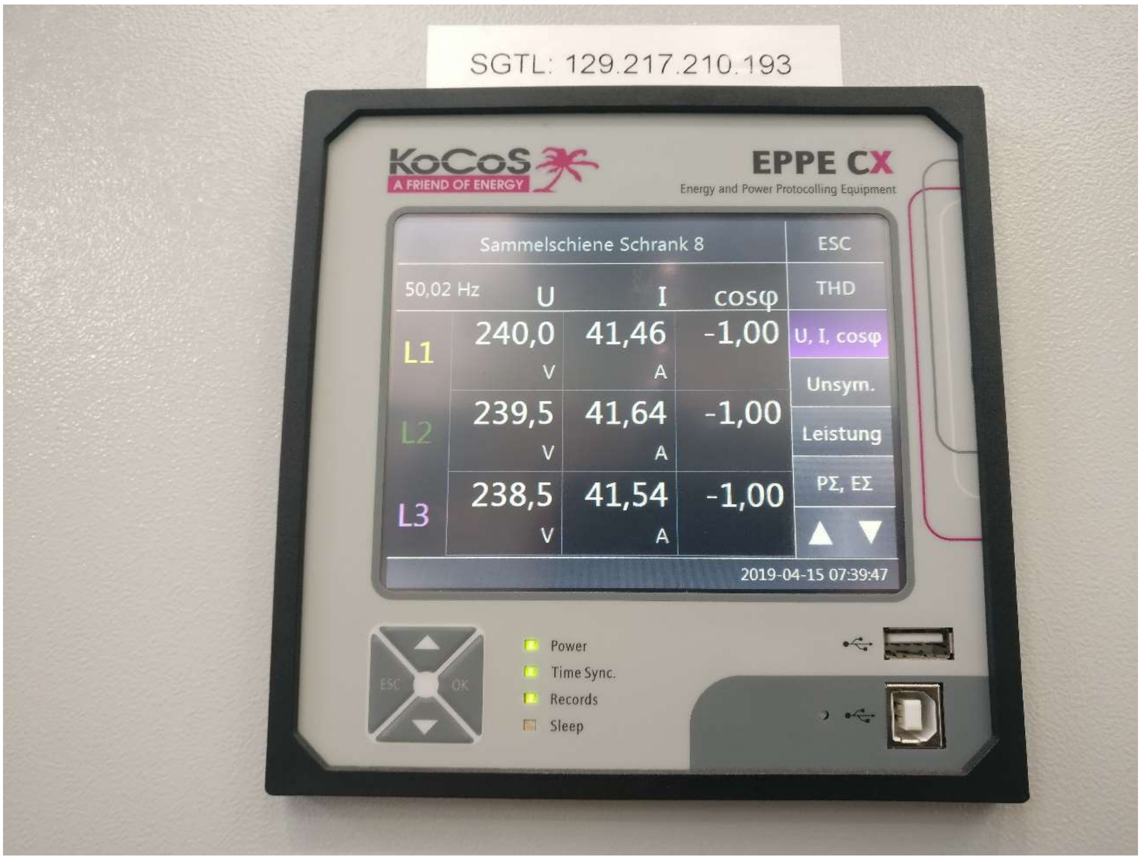

Figure 21. KoCoS EPPE CX Energy and power protocoling equipment

KoCos EPPE CX is high-accuracy power quality analyser, from which detailed technical information can be found at www.kocos.com. KoCoS measurement devices are accessible remotely via Modbus TCP connection. Both of cabinets have an own measurement unit, so we were able to measure voltage and current form two locations of configured test network topology.

4.5 Node-RED programming tool

Programming of the CVC algorithm was done using Node-RED programming tool. Node-RED is a browser-based graphical programming tool that is based on JavaScript programming language. In Node-RED, programs consist of flows that are made by combining different nodes together. Node-RED has large variety of readymade nodes available, but also provides possibility to create custom made function nodes using JavaScript.

Next in this chapter a simple flow is presented as an example of how Node-RED programs are consisted. After the example, different parts of the CVC program are presented. Lastly the user interface of the CVC program is presented. In Figure 22 is presented a simple flow, which allows step position control of the OLTC from browser-based user interface presented in Figure 31.

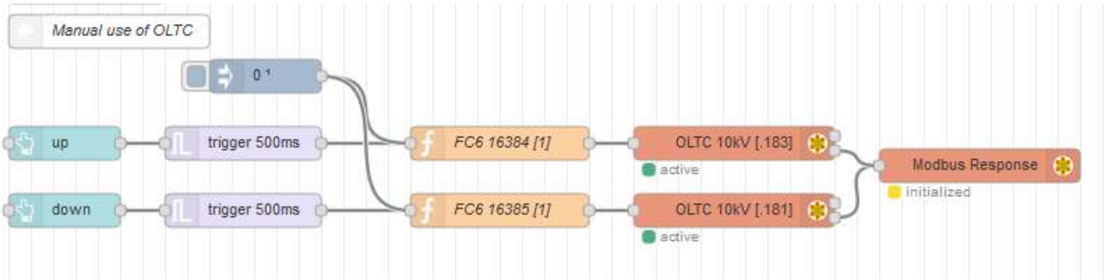

Figure 22. Example of flow in Node-RED

The flow in Figure 22 starts from left and ends to right. The nodes execute their purpose and send outcome to next node. Starting from the left, there are nodes for step position up and down buttons. These are buttons that can be seen in bottom of Figure 30. After these there are purple 500 milliseconds trigger nodes. For step up or down action to occur in the OLTC, the register needs to be written for at least 500 milliseconds. After the trigger node receives message, it sends output of 1 for 500 milliseconds then returns to sending 0. Above trigger nodes is inject node on dark blue. This sends output of 0 once in the beginning of the program. After trigger nodes become function blocks, which determine the register where to and what to write. In the name of function block FC6 stands for writing and 16385 [1] is code for specific register in the device. After function nodes are red Modbus nodes, which determine the device where writing happens. Each device has their own IP address. The last Modbus node is debugging node.

Operation and reading of values of a measurement devices, both of OLTCs and the BES in the laboratory is done using Modbus protocol. Node-RED provides convenient configurable nodes to read and write registers of devices using Modbus protocol. Modbus nodes need to be configured. In order to configure user needs to know IP address and port of device that is meant to be controlled.

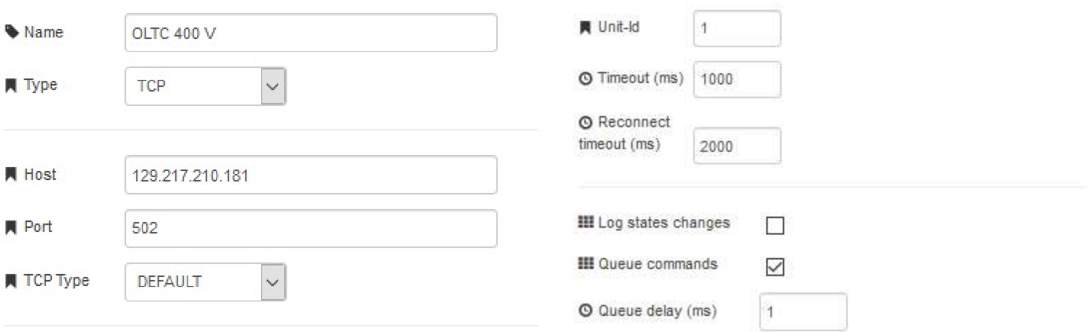

Figure 23. Modbus nodes configuration

Configuration of a Modbus node is show in Figure 23. The host section of configuration has IP address of the connected device. The register where user wishes to write is configured in separate function node.

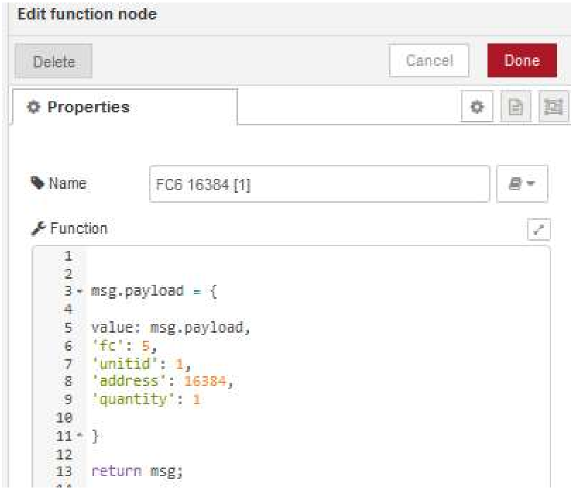

Figure 24. Function nodes configuration

Configuration of function node is show in Figure 24. In configuration fc means to force singe coil and address determines the register where message is written. Quantity determines number of register where message is written. For example, voltage measurements are stored in two registers, so in that case two register have to be read. Unitid is unit identifier, which is not relevant for this application.

In the end, Node-RED programs turned out to be more complex than left to right flow seen in Figure 22. The CVC program that includes operation of the 0.4 kV OLTC and help request sending is presented in Figure 25.

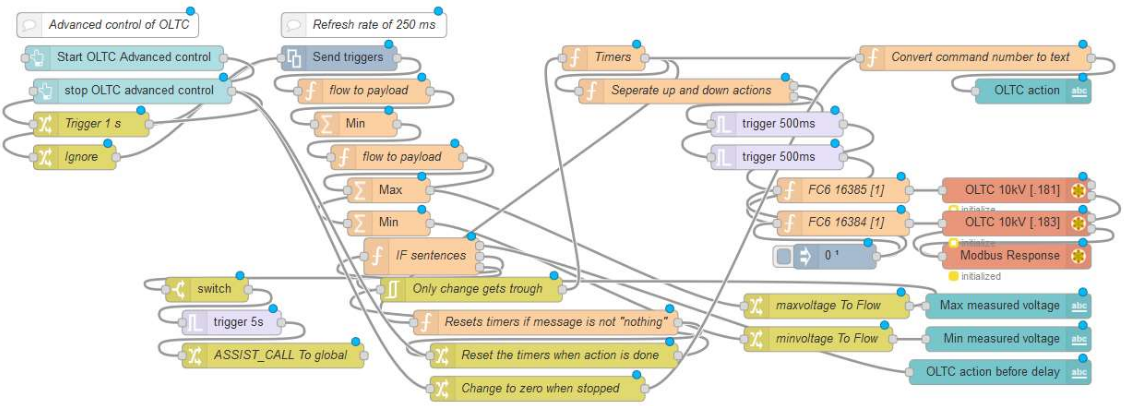

Figure 25. Program for the coordinated voltage control algorithm

The program in Figure 25 has same basic structure as example flow in Figure 22. Flow begins with start and stop buttons, which are used from the user interface. After receiving start button, program starts to send triggers to the flow with refresh rate of 250 milliseconds, which can be stopped by using stop button.

Program executes the logic presented in Chapter 3.2. This begins by calculating the maximum and minimum values from measured voltages. After this, desired state of “assist call” and “control action” is decided. State of “assist call” is read by the program of BES voltage control. Both states are refreshed every 250 milliseconds, however only the change in “control action” effects the function node, which contains the timers.

The “control action” can set timers for step position change to up or down. Both up and down step position changes have two time values, T1 and T2. Both timers T1 and T2 can be simultaneously running for same direction of step position change. Timers for separate direction of step position change can not be running simultaneously. Timers are reset, if measured voltages are within tolerated values.

After timer has run out, timers are reset, and step position of the 10/0.4 kV OLTC is changed. Step position is changed using same basic structure of “trigger node, function node, Modbus node”, seen in example flow of Figure 22. The program in Figure 25 requires control parameters, which are configured in program presented in Figure 26.

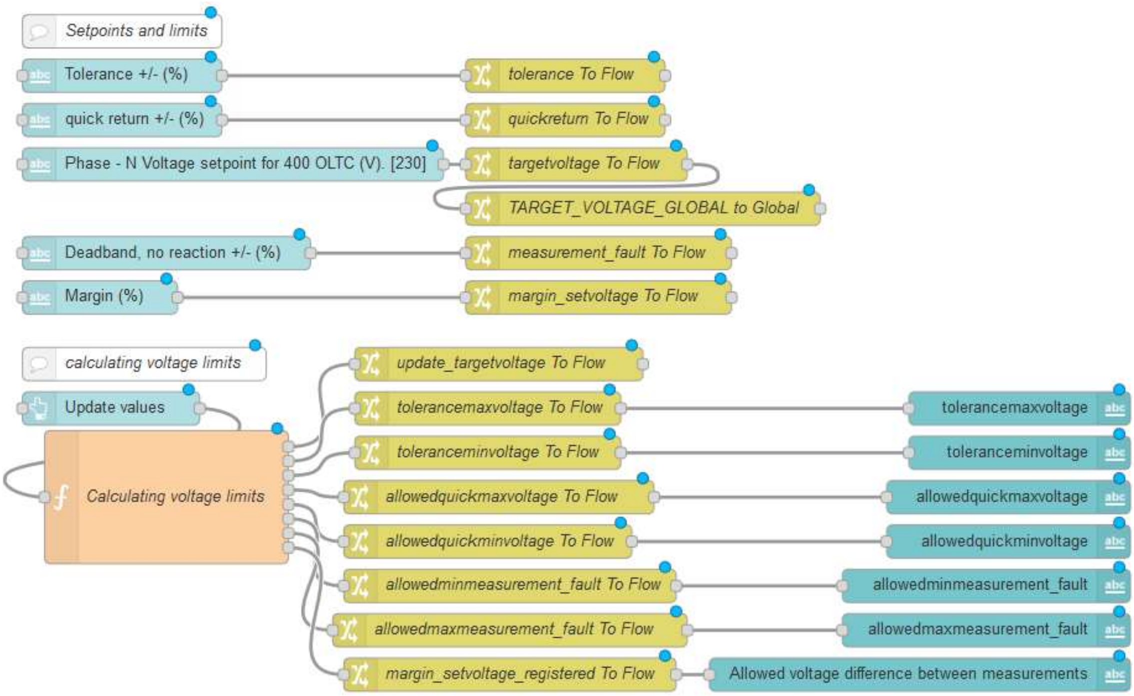

Figure 26. Program to configurate parameters of the coordinated voltage control

Program in Figure 26 has inputs from the user interface for control parameters, from which program calculates values for tolerated and quick return voltages. Inputs are given using user interface input nodes. User calculates and refreshes control parameters using “Update values” button in user interface. Parameters are stored as variables and displayed in user interface. The program that includes operation of BES is presented in Figure 27.

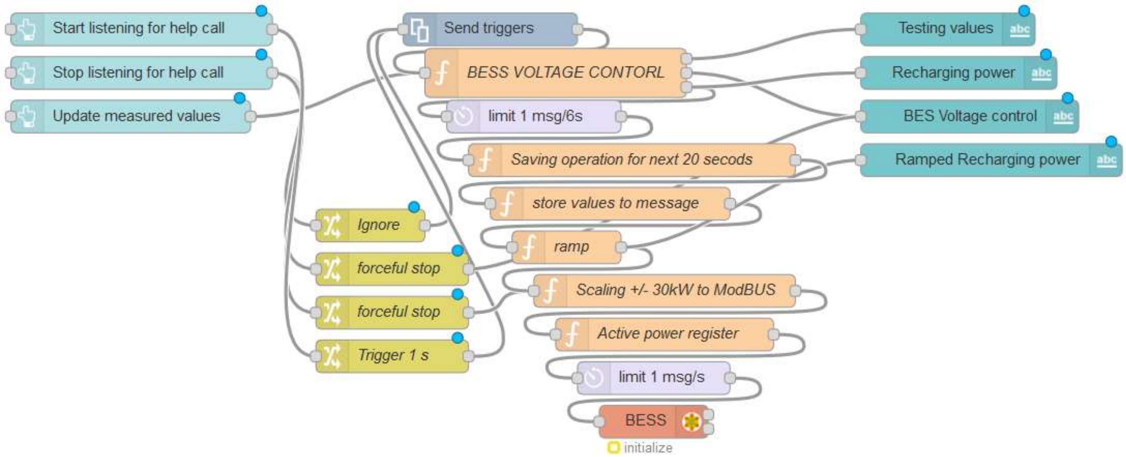

Figure 27. Program for battery energy storage voltage control algorithm

The program in Figure 27 has similar structure as the program of CVC in Figure 25. The voltage control has start and stop buttons that are operated from the user interface. When voltage control is enabled and “help call” is 1, the control logic presented in Chapter 3.4 is executed. Determined control action of the BES is kept on for configurable amount of time. After this, whether the “help call” is 1 is checked again. The control action is sent to the BES using same basic structure of “trigger node, function node, Modbus node”, seen in example flow of Figure 22. The program also sends useful information to user interface. A program for measurement data from the BES is presented in Figure 28.

Figure 28. Program for measurement of battery energy storage

The program in Figure 28 is initiated from the user interface and in which it displays useful information. The program read values from Modbus registers every 1 second and stores them as variables. Similar program is used for measurements for 10/0.4 kV and 10/10 kV OLTCs. The program to create and save data to SQLite databases is presented in Figure 29.

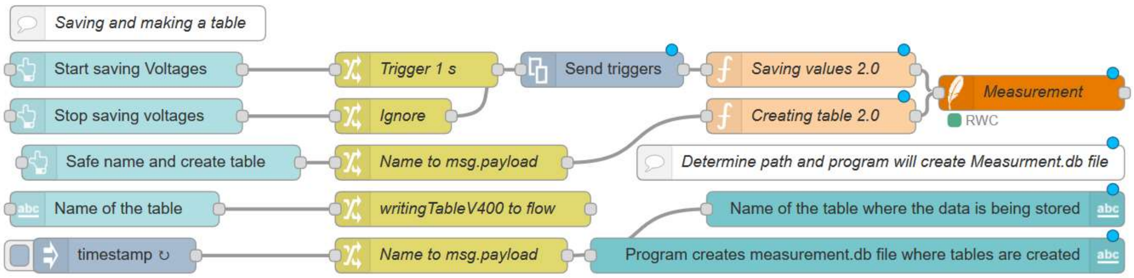

Figure 29. Program to create and save data to SQLite database

The program in Figure 29 has two functions, which can be operated from user interface. User can create SQLite databases with configurable name. User can store values read from Modbus register. Values are stored every second.

One reason why Node-RED proved to be a convenient way of prototyping the CVC was it is convenient way to create and to combine user interface and Modbus communication protocol used in the laboratory. An example of created interfaces are presented in Figure 30 and Figure 31.

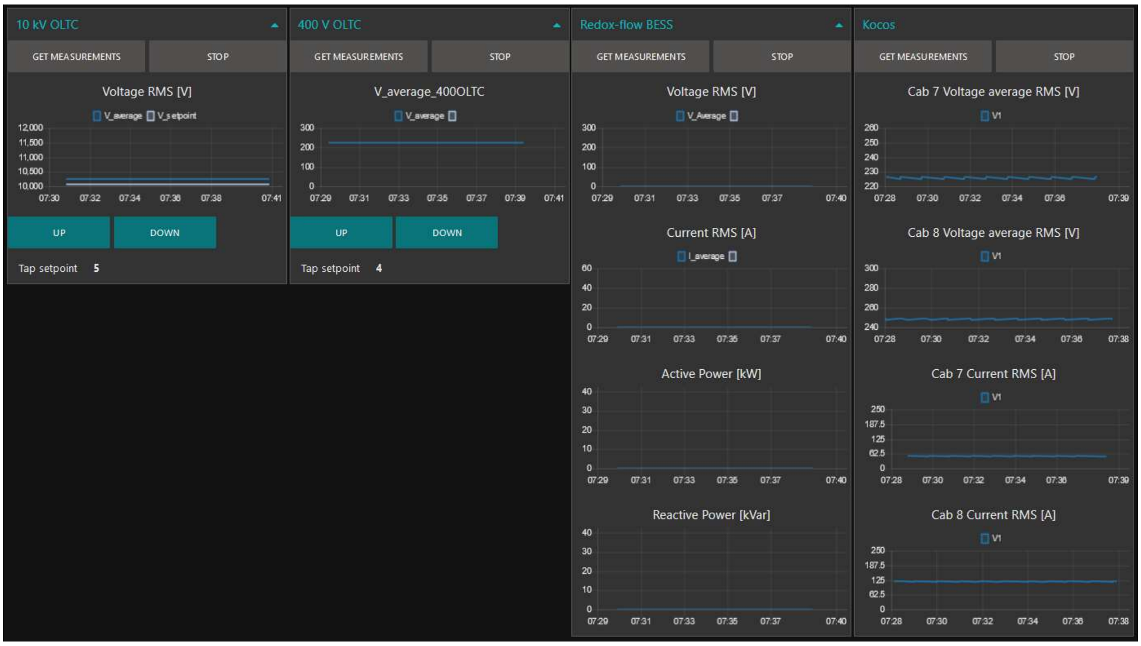

Figure 30. User interface's online measurements section

Interface in Figure 30 is to used establish and read measurements from devices. It was also used to control manually step position of 10/10 kV and 10/0.4 kV OLTC transformers.

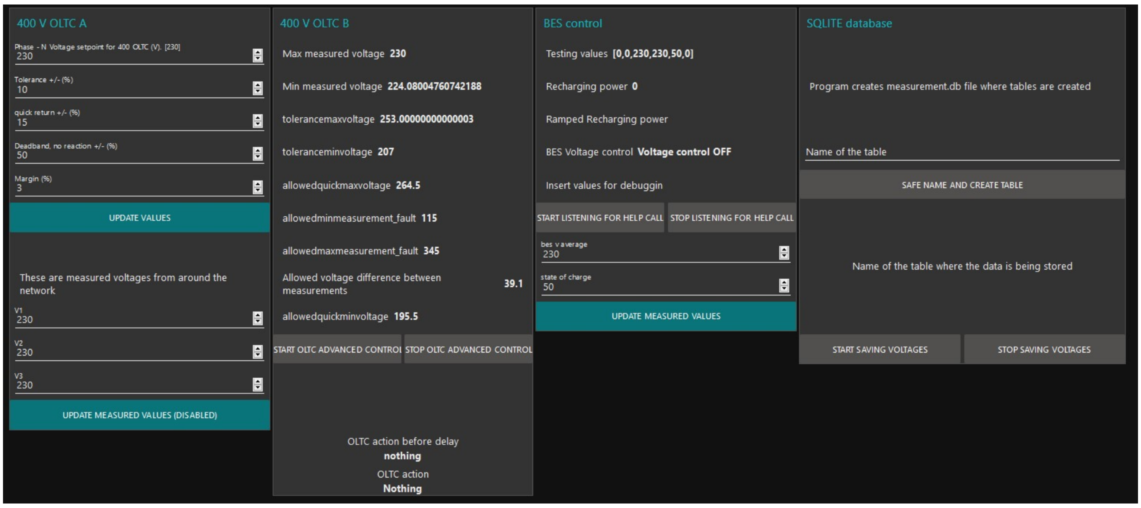

Figure 31. User interface's advanced control section

Interface in Figure 31 is used to set parameters and enable the CVC and the voltage control of BES. It also included possibility to manually insert measurements to test operation of the CVC. It showed the values of control parameters. This interface also enables to create and safe measurement data to SQLite databases.

5. THE EXPERIMENTS AT THE LABORATORY

This thesis compares two control methods in six different test conditions. In this chapter the compared solutions are introduced, the compared test conditions are explained and the methodologies of the experiments are described.

5.1 Compared solutions

The first compared solution included an OLTC at the secondary substation with the fixed set point control method. In this solution control of the OLTC is done using program provided by the supplier of the OLTC, which uses own control logic of the OLTC and takes single voltage measurement from the secondary side of the transformer.

The second compared solution included an OLTC at the secondary substation with the CVC method, which has voltage measurement from the strategic points of network. The CVC coordinates the OLTC and the BES. Strategic points in this case were points with production and the furthest load from the secondary substation. If the voltage difference between the highest and the lowest voltage in the network exceeded the voltage difference between the highest and the lowest tolerated voltage, situation could not be solved with the OLTC. In this case the CVC sends help request to the BES, which will contribute to voltage control

5.2 Compared test conditions

The approach to experiments was to divide changes between experiments into small steps and gradually increase the complexity of the experiments. The goal was to compare control methods in variable conditions. Conditions were following;

- Medium voltage variations without feeders.
- One feeder with load.
- One feeder with production.
- Two different feeders in load and in production.
- MV variations with two different feeders in high load and in high production so that voltage difference exceeds the CVC methods limits.
- MV variations with two different feeders in load and in production.

The first test condition was made to compare the CVC method and fixed set point control in similar actions. Both have voltage measurement from the same point, at the secondary side of the transformer. The diagram of the network topology is presented in Figure 32.

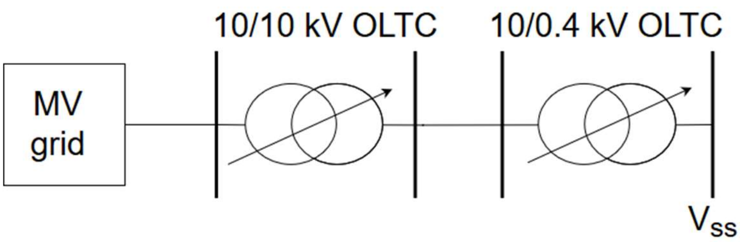

Figure 32. Network topology of test condition: Medium voltage variations without feeders.

Voltage set point for all test conditions was 230 V. Traditional network planning in a grid with the DG is done considering to extreme cases. Maximum load with minimum generation and minimum load with maximum generation [1]. Similar approach was considered creating the second and the third test condition. One feeder with load or production represent these cases. Diagram of the network topology is presented in Figure 33 and Figure 34.

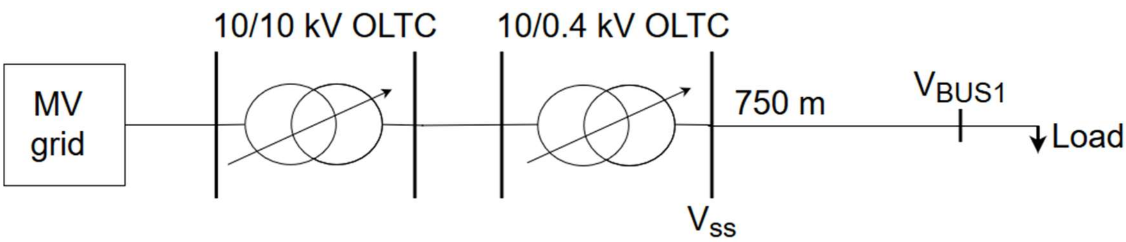

Figure 33. Network topology of test condition: One feeder with load.

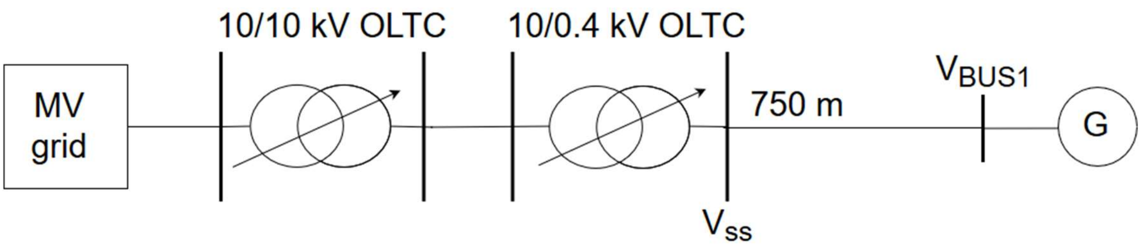

Figure 34. Network topology of test condition: One feeder with generation.

The fourth test condition presents condition, where there is two different feeders in different conditions. Other one has high load and other one has high production. A diagram of the network topology is presented in Figure 35.

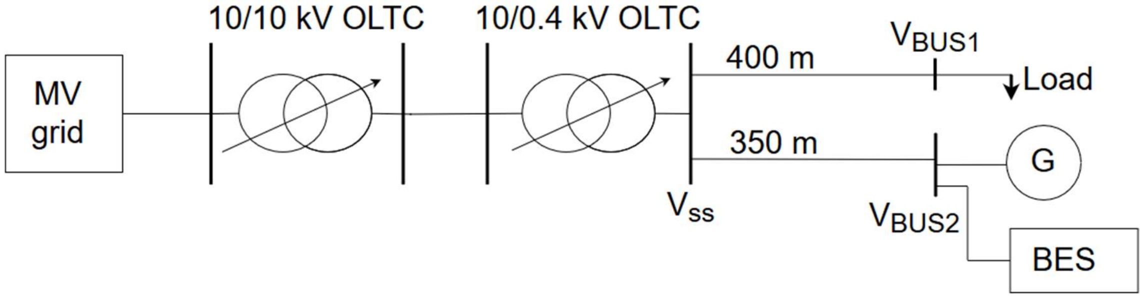

Figure 35. Network topology of test conditions: Two feeders with load and production, Medium voltage variations with two different feeders in load and in production, two different feeders in high load and in high production so that voltage difference exceeds control algorithms limits.

If the voltage difference between these two feeders is too high, it can cause situation where the OLTC can not solve the problem. The fifth test case was to demonstrate this situation. The sixth test condition was made to test control methods in MV variations.

5.3 Methodology of the experiments

The experiments were made using the equipment of the laboratory of TU Dortmund University. Details of the equipment is presented at Chapter 4. Two power amplifiers were used as a load and production. These were operated remotely using their own program. In some of the measurements extra load was provided by the resistor. This was operated locally from the panel of the resistor.

The 10/10 kV OLTC transformer was used to produce medium voltage variations. The transformer was controlled remotely using Node-RED program. The 10/0.4 kV OLTC transformer was used as MV/LV transformer. This transformer was controlled remotely using Node-RED program. Step position 5 served as a starting point for 10/10kV OLTC transformer in medium voltage variation experiments. Step position 5 served also as starting point for 10/0.4 kV OLTC in experiments.

Cable emulator was used to emulate the LV grid. Cable emulator's different lengths of NAYY 4x150 were used as LV cables. Grid protection against faults in the network was accomplished with installed equipment of the laboratory.

Voltage measurement at the 10/0.4 kV secondary side was measured with voltage measurement of the OLTC. Measurement was read using Node-RED program in intervals of 1 second. Voltage and current measurements at BUS1 and BUS2 were measured with Kocos measurement devices. Both OLTCs and Kocos were connected to laboratory's telecommunications network via Modbus. Values were read with same Node-RED program that was used to control devices. Program saved values to SQLite database.

6. RESULTS OF THE EXPERIMENTS

The results of the experiments are presented in this chapter. Control parameters of the OLTC and power amplifiers are presented together with the results, because they varied between measurements. Timer parameters for all measurements were the same. The parameters are presented in Table 3.

	T1 [s]	T2 [s]
Timer values	10	3

Table 3. *Timer parameters*

Timers are same for both CVC and fixed set point control methods.

6.1 Medium voltage variations without feeders

The network topology is presented earlier in Figure 32. Parameters for both control methods are presented in Table 4.

Own control logic of the OLTC			
	%	V_{max} [V]	V_{min} [V]
Tolerance	2	235	225
Quick return	10	253	207
The CVC control			
	%	V_{max} [V]	V_{min} [V]
Tolerance	2	235	225
Quick return	10	253	207

Table 4. *Control parameters*

Control parameters are same for both control methods, because purpose of this test condition is to compare control methods in similar actions. In later cases tolerance value for CVC will be changed to 10%. Operation of control methods in MV rise is illustrated in Figure 36 and Figure 37.

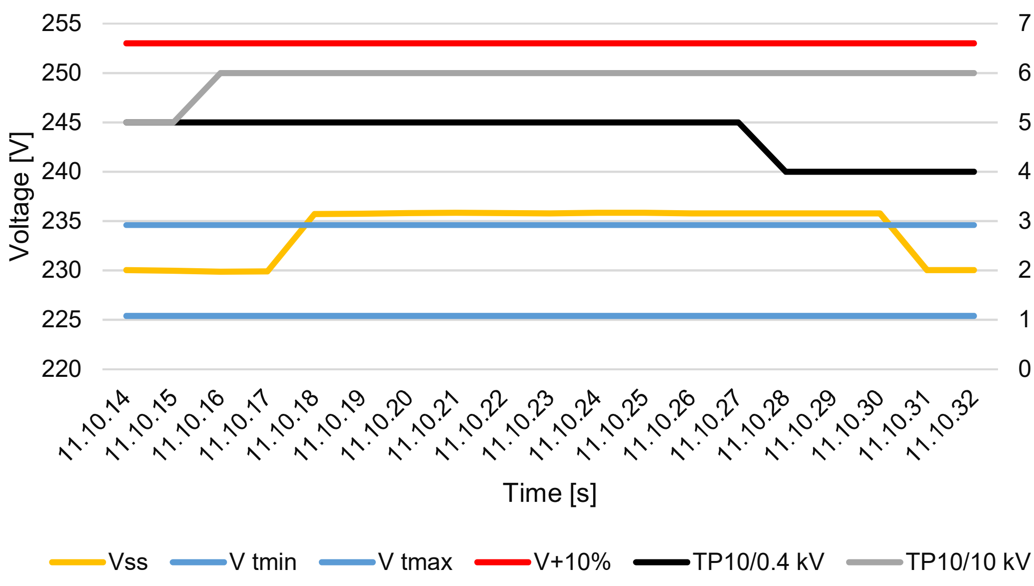

Figure 36. MV voltage rise with fixe voltage set point

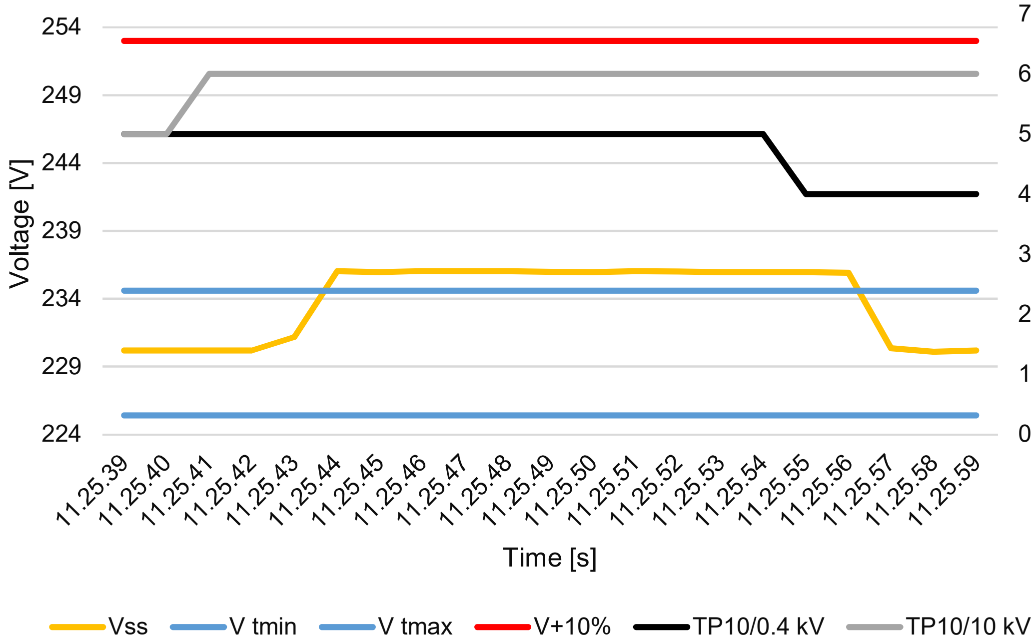

Figure 37. MV voltage rise with CVC

Operation of control methods in MV drop is illustrated in Figure 38 and Figure 39.

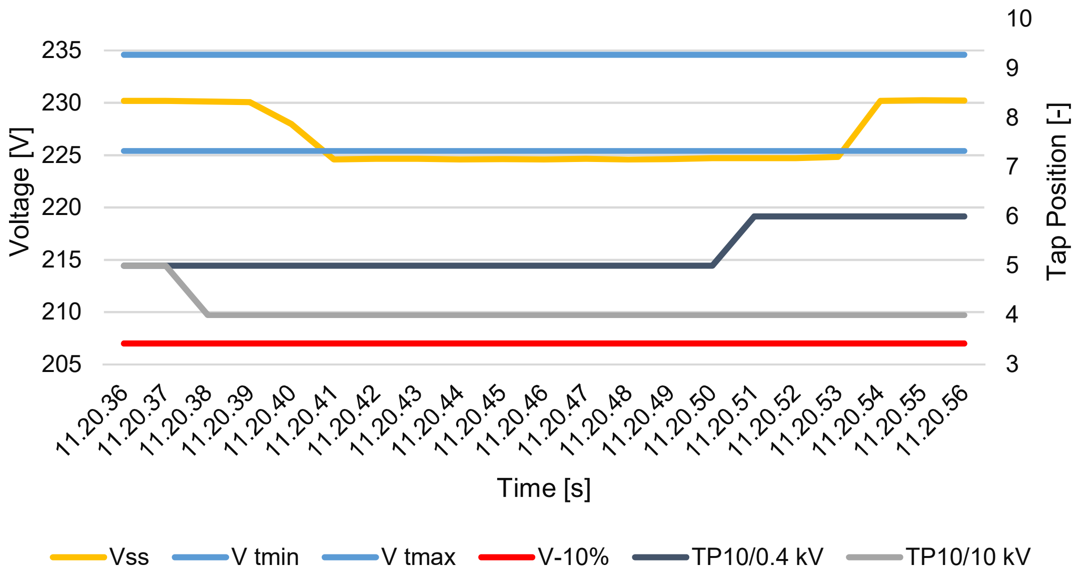

Figure 38. *MV voltage drop with fixed voltage set point*

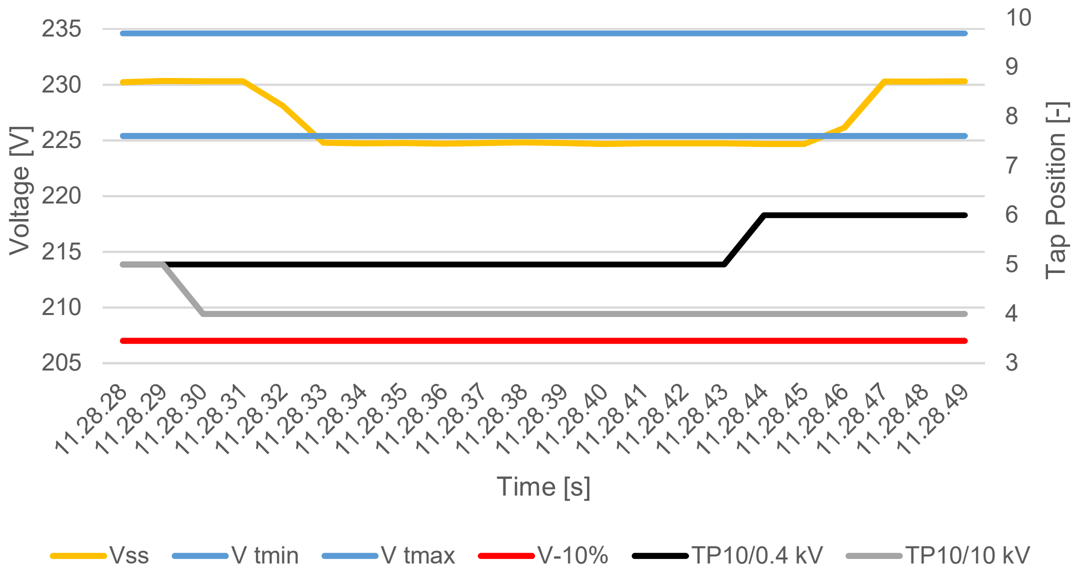

Figure 39. *MV voltage drop with CVC*

Operation of the control methods in higher MV rise is illustrated in Figure 40 and Figure 41.

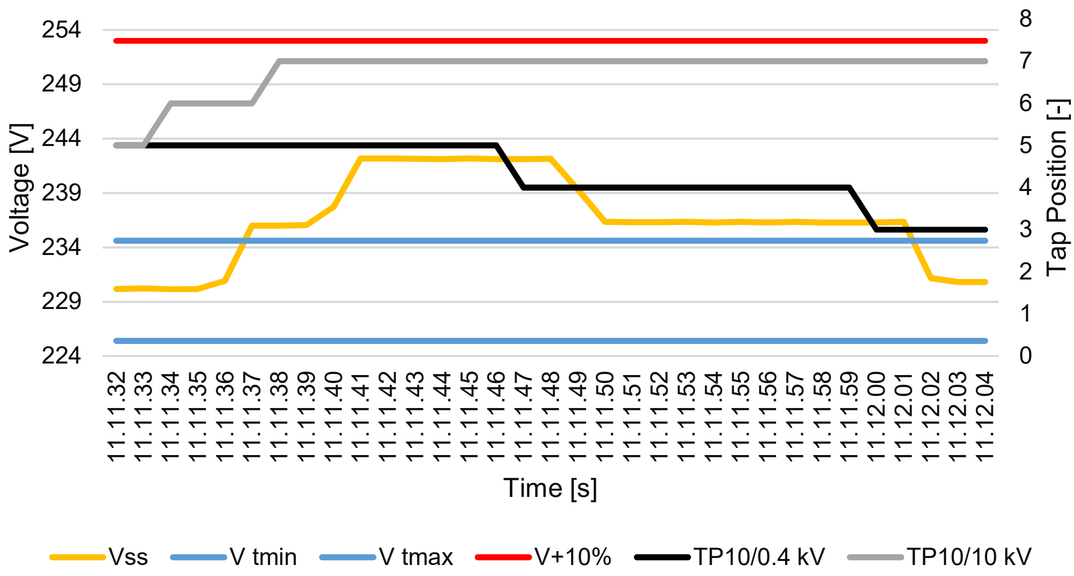

Figure 40. Higher MV voltage rise with the fixed voltage set point

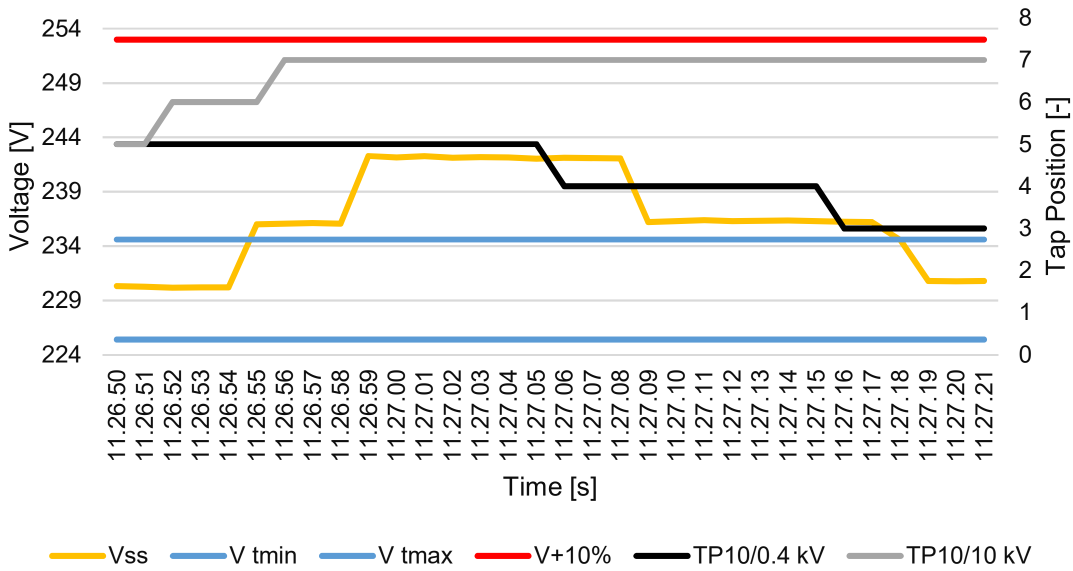

Figure 41. Higher MV voltage rise with CVC

Operation of control methods in higher MV drop is illustrated in Figure 42 and Figure 43.

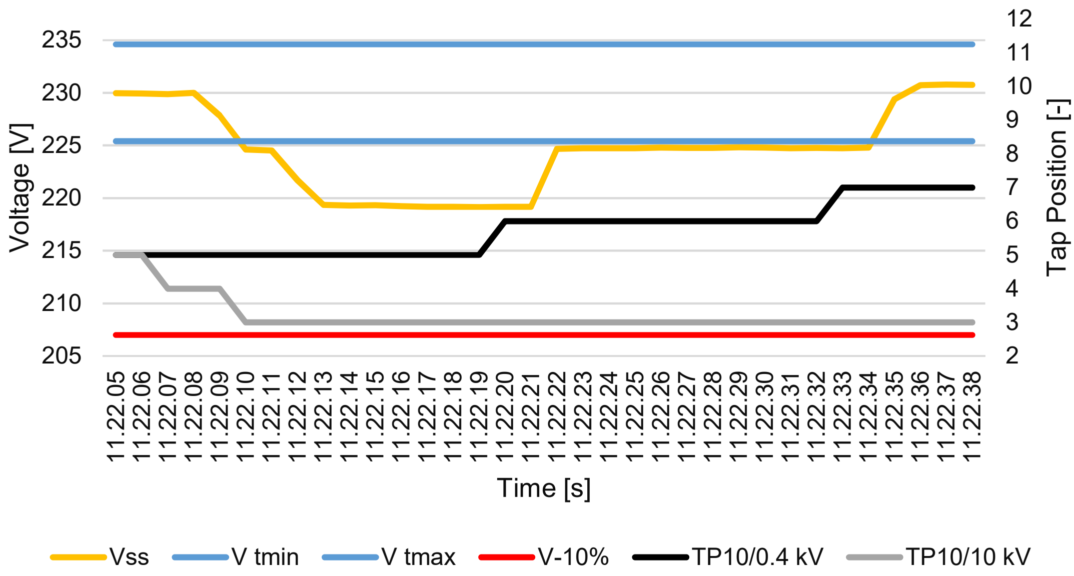

Figure 42. Higher MV voltage drop with fixed voltage set point

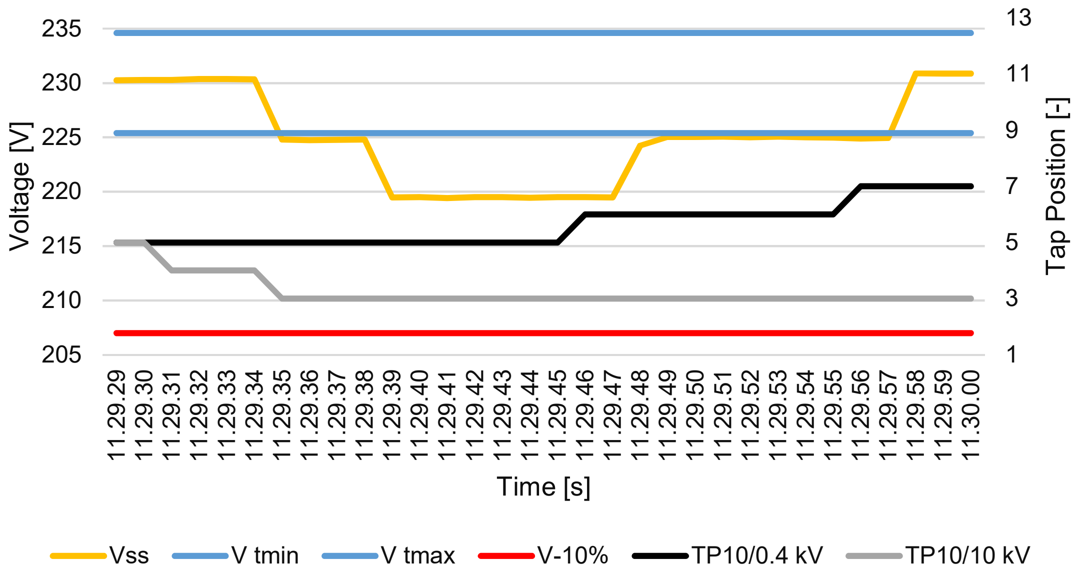

Figure 43. Higher MV voltage drop with CVC

In figures from Figure 36 to Figure 43 *TP10/0.4* kV is tap position of 10/0.4 kV OLTC transformer and *TP10/10kV* is tap position of 10/10kV OLTC transformer. Control methods tolerated maximum V_{Tmax} and minimum voltages V_{Tmin} are drawn in blue. If controlled voltage exceeds these limits, the tap change timer is initiated. In figures from Figure 36 to Figure 43 controlled voltage is secondary substations voltage V_{ss}. Voltage limit of *+/-10%* is drawn in red. Tap position change of 10/10 kV transform is done manually and 10/0.4 kV transformer is controlled by the control method. Value of tap position is read from the OLTC programs registers.

From Figure 36 to Figure 43 we can see that after step position has changed in the register of OLTC, there is a delay before actual step position change is done and effect is seen in the voltage. The maximum and the minimum time differences between the time that step position change is read from register of OLTC and the time that the effect is seen on the voltage are listed in Table 5.

Figure	max[s]	min[s]
36	3	2
37	3	2
38	3	3
39	3	3
40	3	2
41	3	3
42	3	2
43	4	2
Overall	**4**	**2**

Table 5. *The time differences between the time that step position change is read from register of the OLTC and the time that the effect is seen on the voltage.*

From Table 5 we can see that for fixed set point control the time differences are between 2 - 3 seconds and for the CVC time differences are between 2 – 4 seconds. This 2 – 3 second internal delay is one property of the OLTC. The measurement was done once per seconds, so this creates possibility for ± 1 second error in measurement, which could explain why the CVC has 2 – 4 seconds delay and fixed set point control has 2 – 3 seconds.

The total time from the time that the change is seen in the voltage at the substation, to the time until the voltage is restored within tolerated limits is listed in Table 6.

Figure	T1 [s]	Second T1 [s]	Delay[s]	Total time until the voltage is restored within tolerated limits [s]
36	10	-	3	13
37	11	-	2	13
38	10	-	3	13
39	11	-	3	14
40	10	13	2	25
41	11	10	3	24
42	10	13	3	26
43	11	10	2	23

Table 6. *Total time that it took to return voltage within tolerated limits*

In Table 6 the total time it took to return voltage within tolerated values consist of T1, second T1 and the delay. The T1 in Table 6 is time it took for the control method to initiate step position change from the time the voltage had exceeded the tolerated values. In Figure 40, Figure 41, Figure 42 and Figure 43 there was two tap changes. The time between first tap change was initiated to the time that second tap change was initiated is listed as “Second T1”. The delay in Table 6 is time difference between the time that the last step position change was initiated to the time that the voltage was returned to tolerated value.

The first T1 was consistently 10 seconds for the fixed set point control and 11 seconds for the CVC. Value of T1 parameter in the CVC is 10 seconds. The CVC has measuring interval of 1 second and program has refresh time of 250 milliseconds. The Modbus communication worked reliably, if the CVC kept control command on for step position change for 500 milliseconds. This was kept as a precautionary measure instead of exact time value; therefore, the impact is between 0 – 500 milliseconds. These may explain the 11 seconds instead of 10 seconds; however, the difference is also within the error margin of the 1 second due the measuring interval.

The second T1 was consistently 13 seconds for the fixed set point control and 10 seconds for the CVC. The is not within the error margin of ±1, however 13 seconds may be explained with 3 second internal delay of logic of the OLTC. This would be in line with the 2 - 3 second delay it takes from initiating step change to the actual step change.

The difference between the first T1 and the second T1 of the CVC is between the error margin of ±1. However, the CVC has 1 second measuring interval. The measured value is stored as variable. This variable is used to determine whether to initiate timer. In case of second T1 this variable is already over the tolerated values and this neglects the 1 second measuring interval, which may explain the difference between the first and the second T1.

Timer T1 was set to 10 second to test and compare behaviour of algorithms. However, in real life applications this would most likely be longer. Even the total time of restoring voltage within tolerated limits varied between the fixed set point control and the CVC, the variation would become increasingly insignificant if T1 was longer.

This test condition was made to compare behaviour of both control methods in similar actions. The results demonstrate that the CVC and the fixed set point control actions were similar. In order to test similar actions of control methods, the tolerance of CVC was set to be the same as for fixed set point control. In real application of CVC this would not be the case. Tolerance would be set to the tolerated limits of network, +/-10%, which is the case for later experiments this thesis.

6.2 One feeder with load or production

This test condition was made to compare the two different control algorithms in load and production condition of one feeder. Network topology of the experiments are presented in Figure 33 and Figure 34. Parameters of OLTC own control algorithm and load values are presented in Table 7.

Own control logic of the OLTC			
	%	V_{max} [V]	V_{min} [V]
Tolerance	2	235	225
Quick return	10	253	207
The CVC control			
	%	V_{max} [V]	V_{min} [V]
Tolerance	10	253	207
Quick return	15	265	196
Margin	3		
Load values			
Resistor	101	kW	
Amplifier	30	kW	
Total	131	kW	
Production values			
Amplifier	70	kW	

Table 7. *Control parameters and load values*

Value for resistor in Table 7 is the nominal value of the resistor. It is a resistive component and dependant on the voltage of the network. Therefore, actual power was lower, because voltage at V_{bus1} was below nominal voltage of 230 V. Nevertheless, this does not change the setup of the measurement, since here we are interested in voltage values, which were measured directly. Results for loading condition with one feeder are presented in Figure 44 and Figure 45.

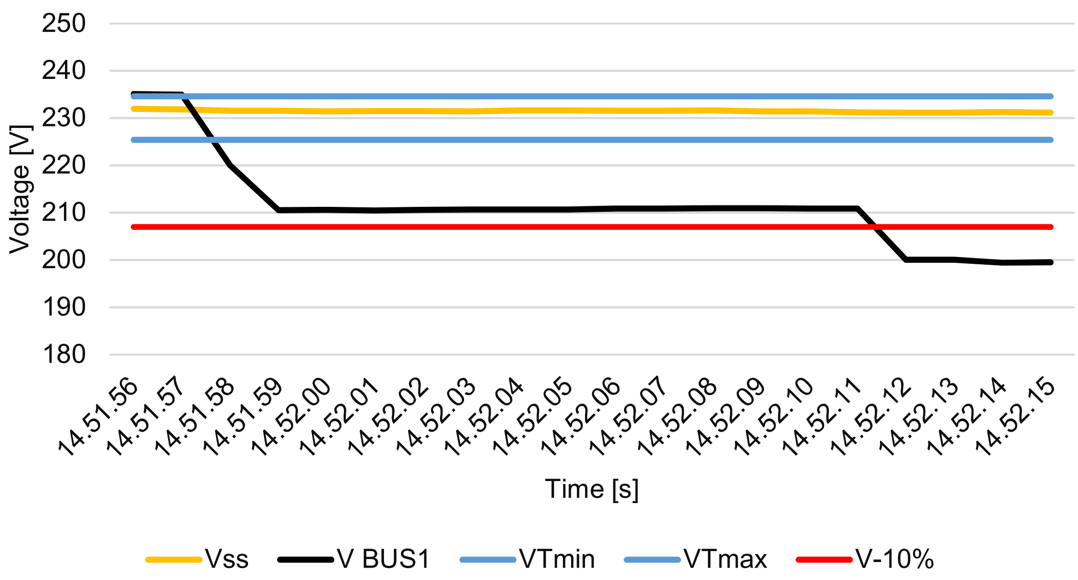

Figure 44. Load variation with fixed set point

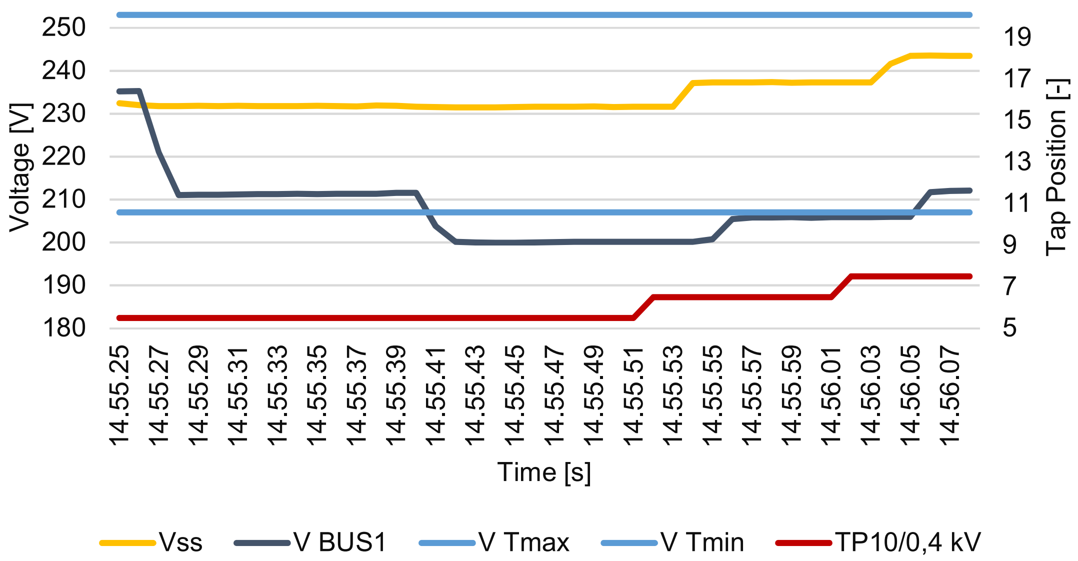

Figure 45. Load variation with CVC

TP10/0.4 kV in Figure 44 and Figure 45 is tap position of 10/0.4 kV OLTC transformer. Control methods tolerated maximum V_{Tmax} and minimum voltages V_{Tmin} are drawn in blue. Tap change timer is initiated, if controlled voltage exceeds these limits.

For Figure 44 and Figure 46, the controlled voltage is the secondary substations voltage V_{ss}, voltage. For Figure 45 and Figure 47, the controlled voltage is the secondary substations voltage V_{ss}, voltage, voltage at bus 1 V_{BUS1} and voltage at bus 2 V_{BUS2}. In Figure 44 voltage limit of *+/-10%* is drawn in red. The load in experiments of Figure 44 and Figure 45 was gradually increased, first connecting the resistor 101 kW and then the power amplifier 30 kW.

From results in two figures above one can see that voltage variation caused by load that is far away from transformer can cause voltage violation. With CVC this problem is detected, and voltage is restored within tolerable limits. The results of both control methods in production condition of one feeder are presented in Figure 46 and Figure 47.

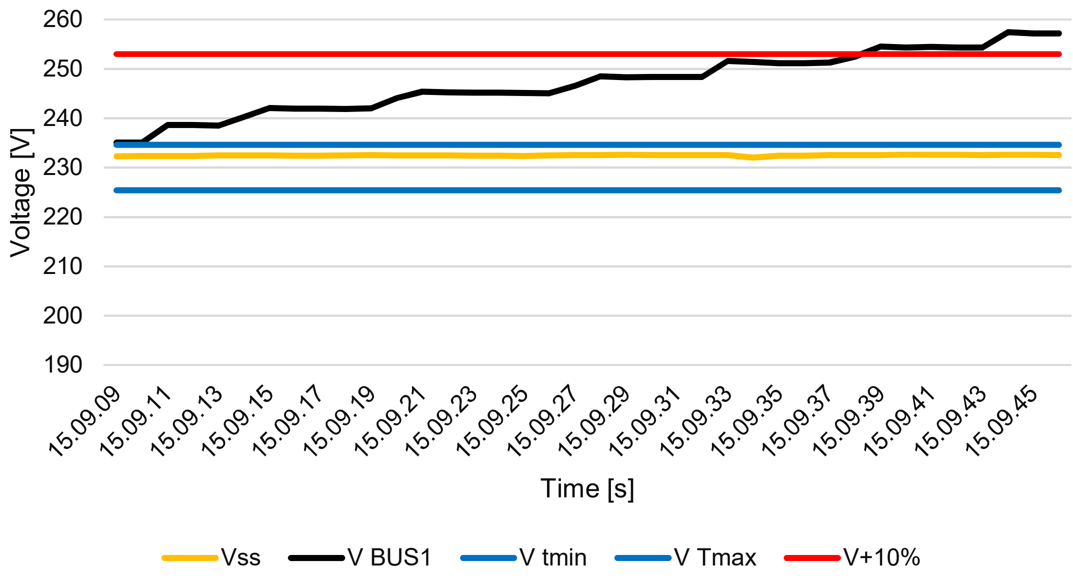

Figure 46. Production with fixed set point

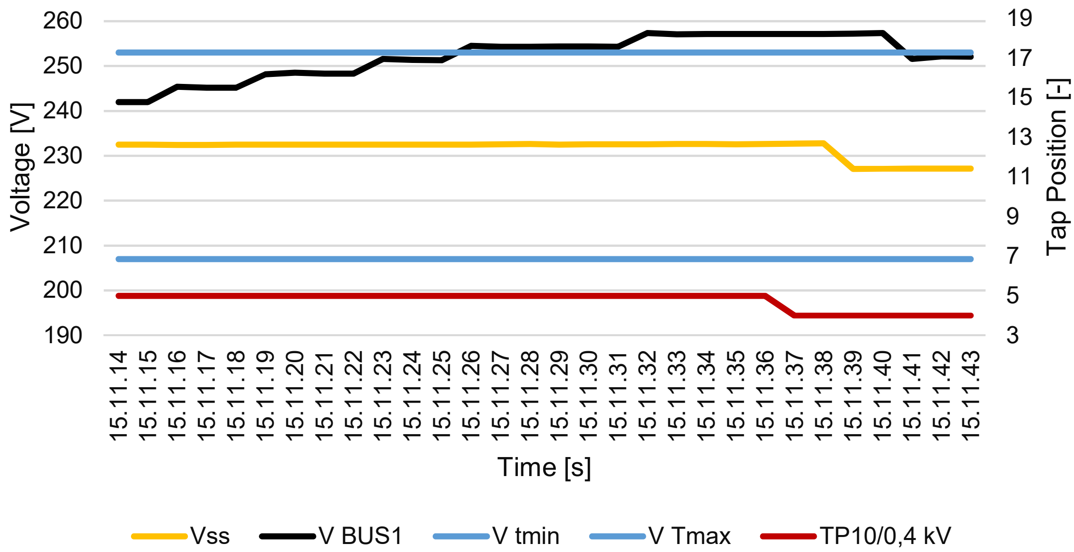

Figure 47. Production with CVC

Due the restrictions of the power amplifiers, the power had to be increased gradually. Therefore, in Figure 46 and Figure 47, the production of power amplifier is gradually increased to 70 kW. The effect of this production to voltage can be seen in V_{BUS1}. In

Figure 47 the first part of gradual increase from 0 kW is cut off for better scaling of the picture.

The results presented in this chapter demonstrate that variation in voltage caused by load or production that is far away from transformer can cause voltage violation at the customer supply point. With the CVC this problem can be solved, which can be seen in Figure 45 and Figure 47. Figure 44 and Figure 46 demonstrate that fixed set point control was not able to detect voltage violation. This is due that effect of high load or production far away from transformer has minor impact on voltage at the transformer.

6.3 Two different feeders in load and in production

This test condition was made to compare the two different solutions in a network that has two different feeders in load and in production. Network topology is presented in Figure 35. Parameters of OLTC own control algorithm and production values are presented in Table 8.

Own control logic of the OLTC			
	%	V_{max} [V]	V_{min} [V]
Tolerance	1.6	234	226
Quick return	8	248	212
The CVC control			
	%	V_{max} [V]	V_{min} [V]
Tolerance	8	248	212
Quick return	12	258	202
Margin	2.4		
Load values			
Amplifier	80	kW	
Production values			
Amplifier	92	kW	

Table 8. *Experiments parameters for two feeders with production and load condition*

Tolerance had to be scaled down for these experiments, because power amplifiers were at their power limit. To create conditions, with large enough voltage difference between busses, control parameters were scaled down 20%. The load and production values were same for both measurements, but voltage did not reach over +8% limit in the experiment with the fixed set point.

Scaling down parameters is justified because the operation of control methods would be the same, if components would have more rated power and parameters would have not been scaled down. However, OLTC is a discrete component and voltage difference between two steps comes as a limiting factor for scaling parameters down. This would become problem for OLTC with fixed control. If tolerated bandwidth for voltage would be smaller than voltage difference between two steps, OLTC would end up doing step changes continuously. Scaling down by 20% was chosen taking this and rated powers of components into consideration.

Results for two different feeders in load and production are presented in Figure 48 and Figure 49.

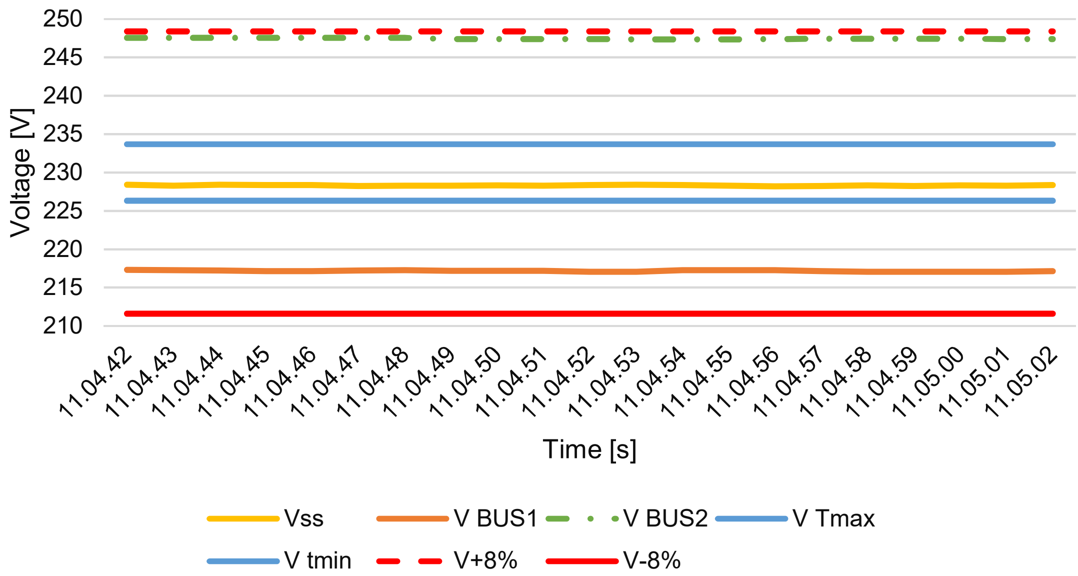

Figure 48. *Fixed set point with two different feeders in load and in production*

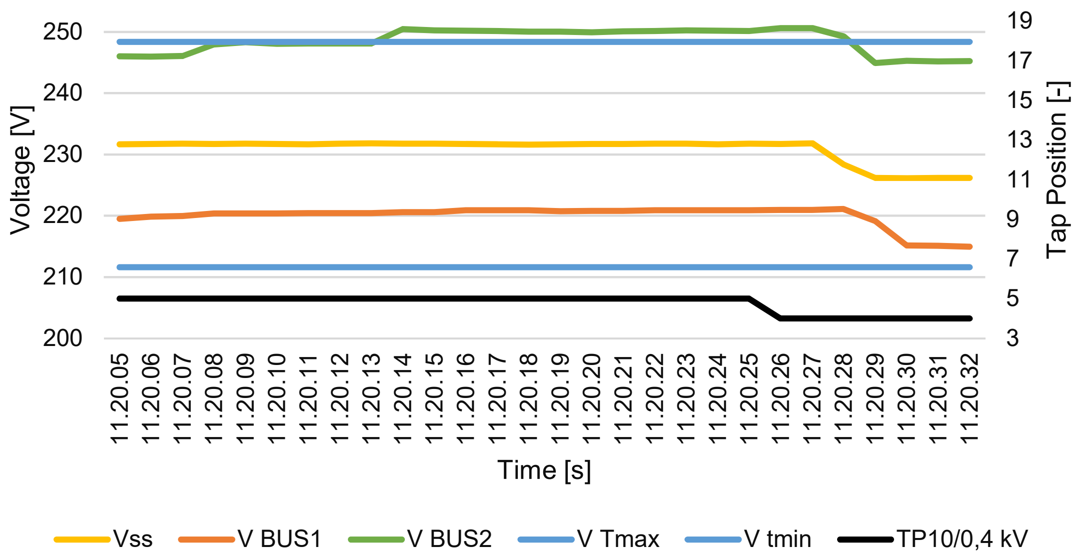

Figure 49. *Advanced control with two different feeders in load and production*

TP10/0.4 kV in Figure 48 and Figure 49 is tap position of 10/0.4 kV OLTC transformer. Control methods tolerated maximum V_{Tmax} and minimum voltages V_{Tmin} are marked in blue. If controlled voltage exceeds these limits, tap change timer is initiated. For Figure 48, the controlled voltage is the secondary substations voltage V_{ss}, voltage. For Figure 49 the controlled voltage is the secondary substations voltage V_{ss}, voltage, voltage at bus 1 V_{BUS1} and voltage at bus 2 V_{BUS2}. In Figure 48 voltage limit of ± *8%* is drawn in red.

Again, due the restrictions of the power amplifiers, the power had to be increased gradually. Therefore, In Figure 49 the production of power amplifier is gradually increased to

92 kW. The effect of this production to voltage can be seen in V_{BUS2}. In Figure 48 and Figure 49 part of gradual increase from 0 kW is cut off for better scaling of the picture.

The results in Figure 48 demonstrate that condition of two different feeders in load and production could be able to cause voltage violation that would be left unnoticed by fixed set point control method. Slight increase at production would cause voltage violation. Results in Figure 49 demonstrate that with the CVC voltage variation would be detected and measured voltages would be returned to the tolerated limits.

6.4 Two different feeders in high load and in high production, so that the voltage difference exceeds limits of the control method

This test condition was created to test cooperation of the OLTC and the BES using the CVC method. Network topology is presented in Figure 35. Parameters of the CVC, load and production values are presented in Table 9.

The CVC method			
	%	V_{max} [V]	V_{min} [V]
Tolerance	8	248	212
Quick return	12	258	202
Margin	2.4		
Load values			
Amplifier	35	kW	
Resistor	100	kW	
BES Charging	30	kW	
Production values			
Amplifier	92	kW	

Table 9. *Control parameters for case with two different feeders in high load and in high production so that voltage difference exceeds control algorithms limits*

Results are presented in Figure 50 and Figure 51.

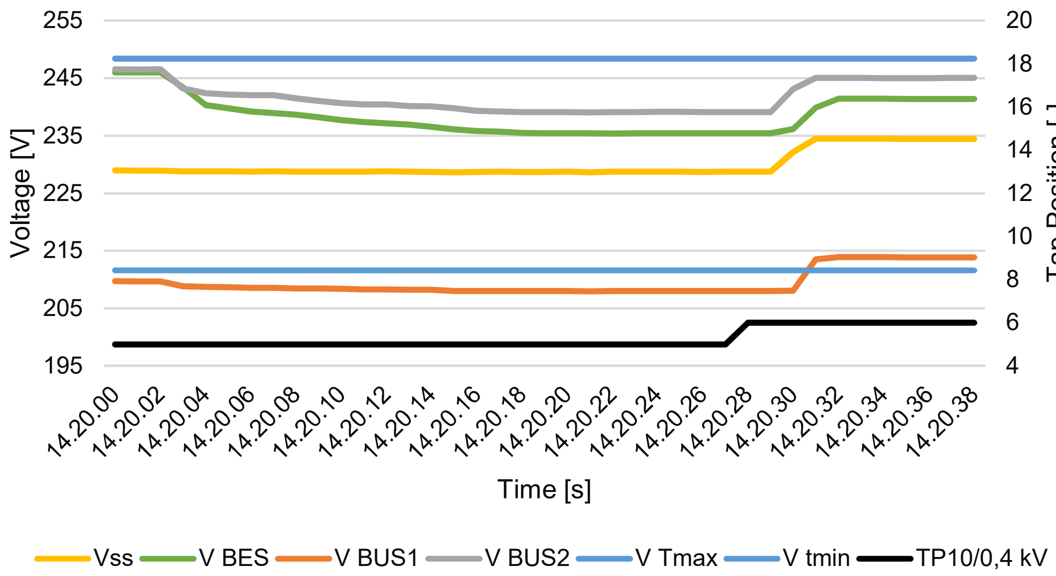

Figure 50. *CVC with two different feeders in load and production, with BES*

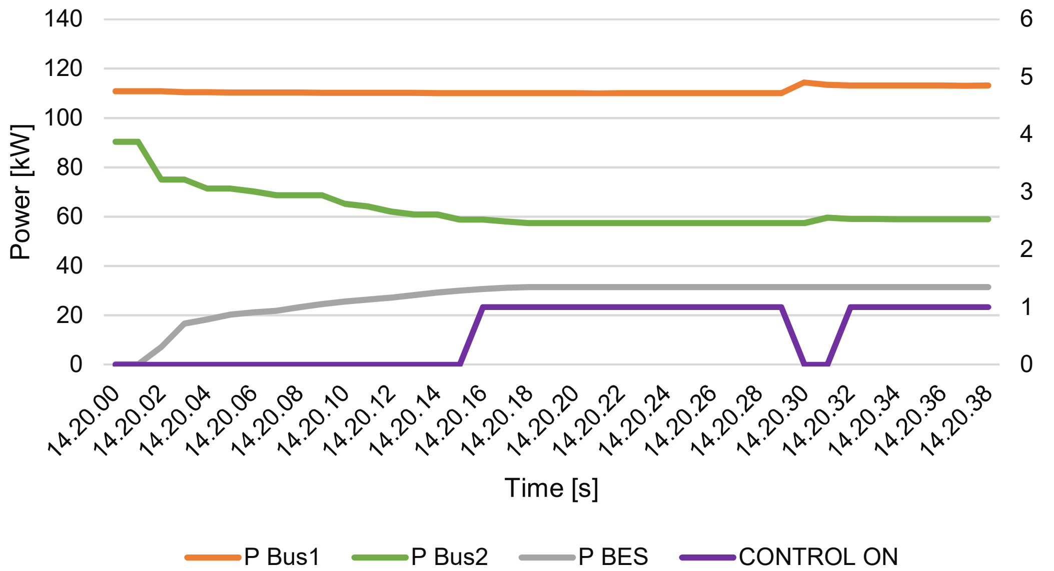

Figure 51. *CVC with two different feeders in load and production, with BES*

Figure 50 and Figure 51 present results of same experiment. Voltages and tap position change are shown in Figure 50. Powers and whether the CVC gives the OLTC permission to do tap changes is shown in Figure 51. Whether the CVC gives the OLTC permission to do tap changes is determined by Equation (12) in Figure 10 at Chapter 3.2 .

Tap position of 10/0.4 kV transformer *TP10/0.4* kV is drawn in black. Tolerated maximum V_{Tmax} and minimum voltages V_{Tmin} are marked in blue. If controlled voltage is exceeding these limits, tap change timer is initiated. For Figure 50 controlled voltage is voltage at secondary substation V_{ss}, voltage at bus 1 V_{BUS1} and voltage at bus 2 V_{BUS2}. Power values measured from busses P_{BUS1} and P_{BUS2} are drawn in Figure 51. *P_{BUS1} is power flow to the bus and P_{BUS2} is power flown from the bus.* P_{BES} is power which BES recharges. *CONTROL ON* in Figure 51 is indicator, where CVC allows OLTC to do tap changes or not. The redox flow energy storage is connected to the busbar 2 at the connection cabinet (Figure 20) by a cable. With high power this causes the voltage drop in this cable causes voltage difference between V_{BUS2} and V_{BES} in Figure 50.

Before moment 14:20:12 voltage difference between measured the maximum and the minimum value of voltage is too high for OLTC to be able to fix situation. If it would do step up operation, voltage would exceed maximum tolerated voltage and OLTC would end up doing continuously tap changes, i.e. hunting behaviour.

The CVC sends help request for BES at 14:20:02. In this test condition, there is BES connected in same bus which has high production. After receiving help call BES starts to recharge in order to bring voltage V_{BUS2} down. At 14:20:16 voltage has come down enough for the OLTC do initiate the timer for tap change. At 14:20:31 voltages are restored within tolerated limit after the step-up operation of OLTC.

Results in this chapter demonstrate that the CVC with cooperation of an OLTC and a BES can solve situation which the CVC with only an OLTC would not be able to solve. However, there are constrictions to using a BES for voltage control. Whether a BES can contribute enough load or production for voltage control is situational. It depends on the network topology, production in the network, load in the network, use purpose of a BES and state of charge of a BES. If a BES is already full, it cannot contribute as a load and vice versa.

6.5 Medium voltage variations with two different feeders in load and in production

The network topology is presented in Figure 35. Parameters of the both control methods and production values are presented in Table 10.

Own control logic of the OLTC			
	%	V_{max} [V]	V_{min} [V]
Tolerance	2	235	225
Quick return	10	253	207
The CVC control			
	%	V_{max} [V]	V_{min} [V]
Tolerance	10	253	207
Quick return	15	265	196
Margin	3		
Load values			
Amplifier	80	kW	
Production values			
Amplifier	92	kW	

Table 10. *Control parameters for MV variations with two different feeders in load and in production*

Tolerance is not scaled down for these experiments. Results are presented in Figure 52, Figure 53, Figure 54, Figure 55, Figure 56, Figure 57, Figure 58 and Figure 59.

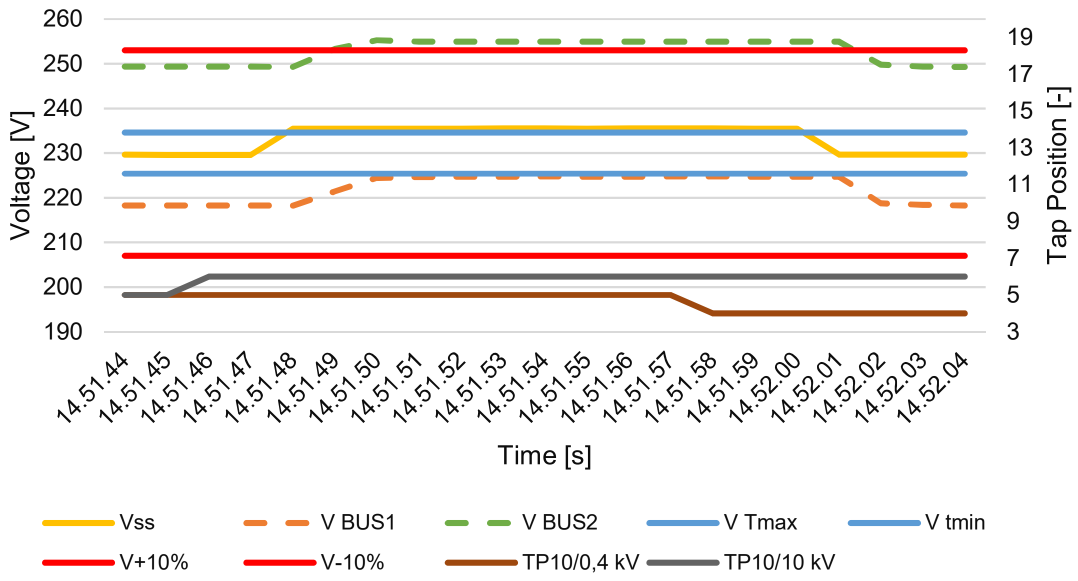

Figure 52. MV voltage rise effect to two different feeders in load and production, fixed set point

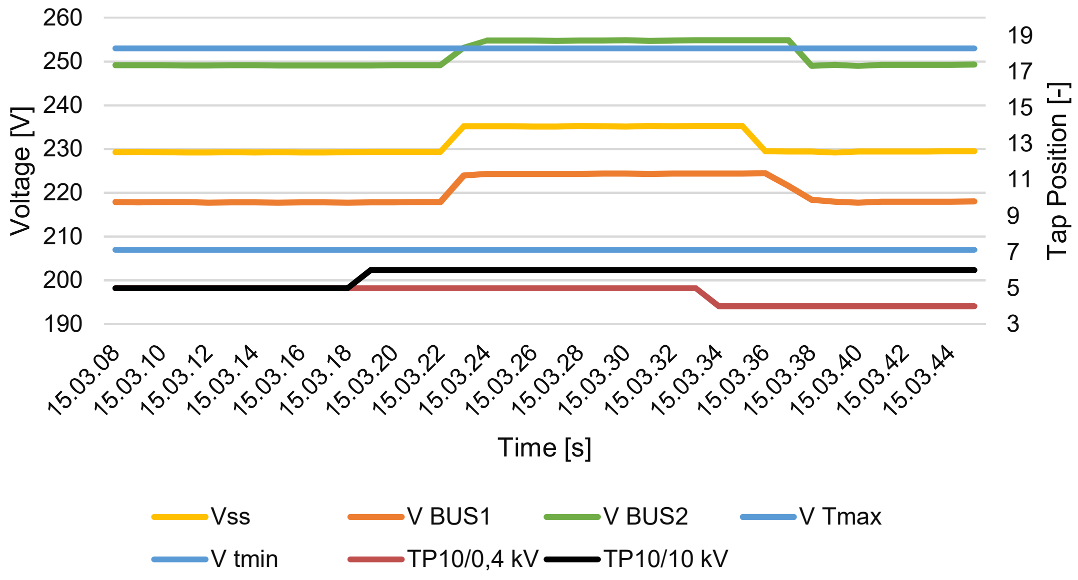

Figure 53. MV voltage rise effect to two different feeders in load and production, CVC

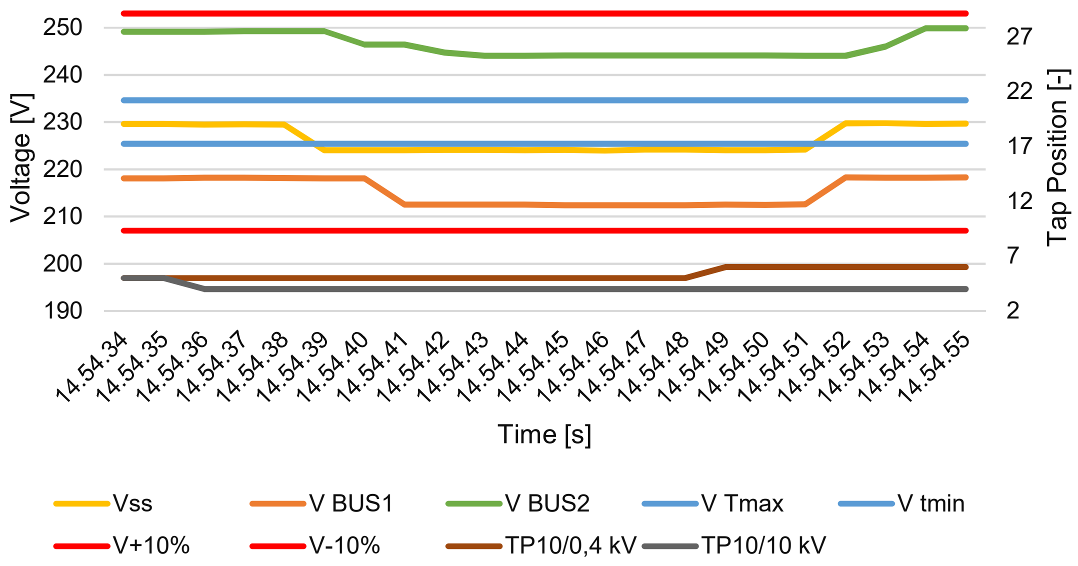

Figure 54. MV voltage drop effect to two different feeders in load and production, fixed set point

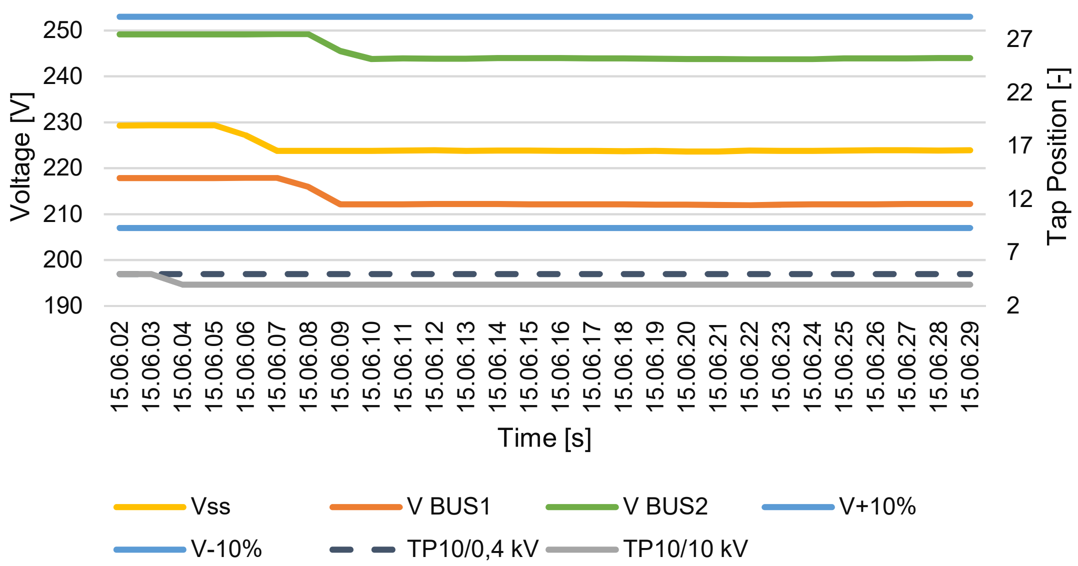

Figure 55. MV voltage drop effect to two different feeders in load and production, CVC

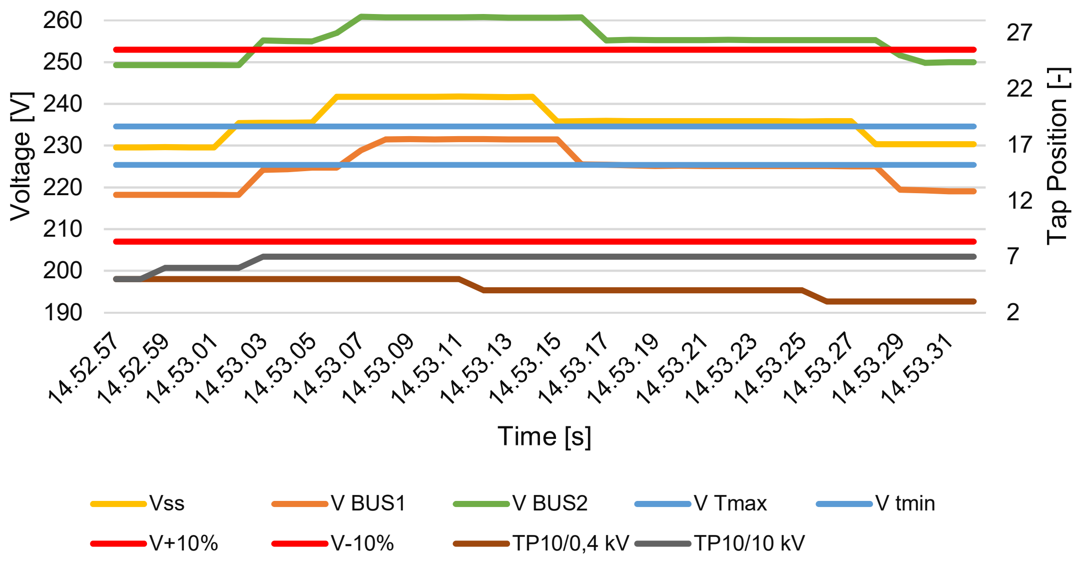

Figure 56. Higher MV voltage rise effect to two different feeders in load and production, fixed set point

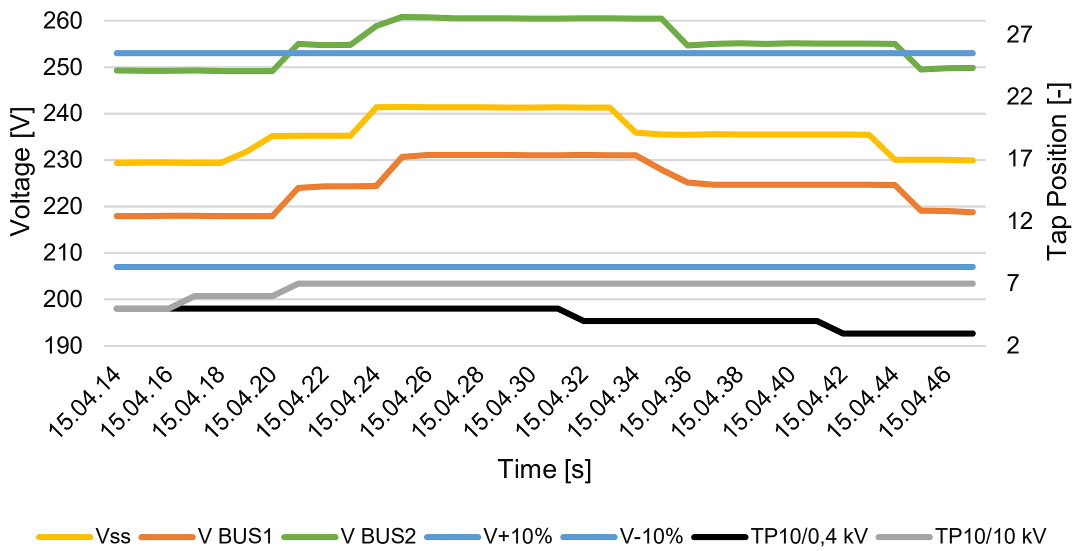

Figure 57. Higher MV voltage rise effect to two different feeders in load and production, CVC

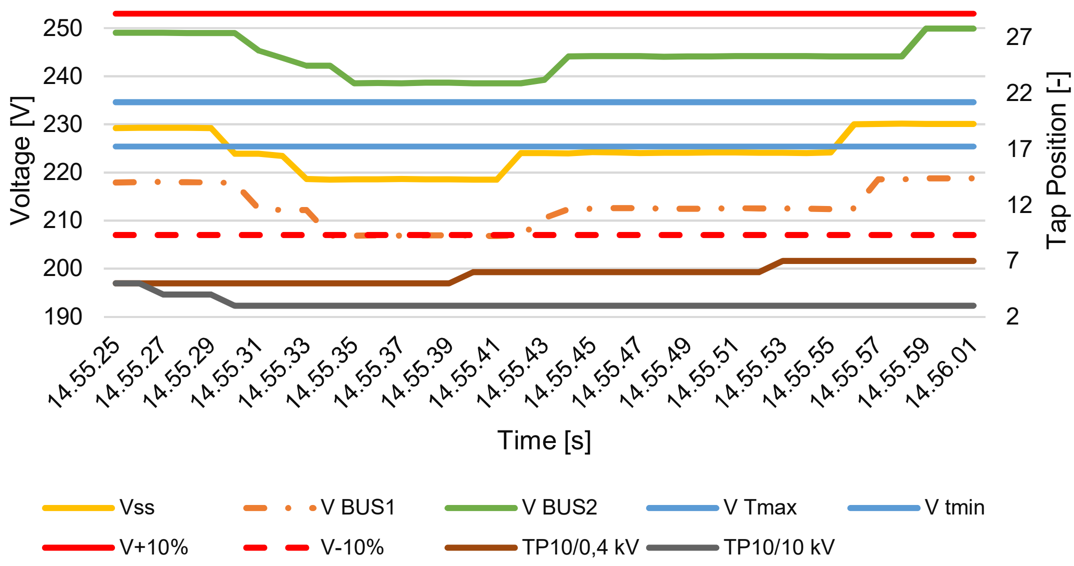

Figure 58. Higher MV voltage drop effect to two different feeders in load and production, fixed set point

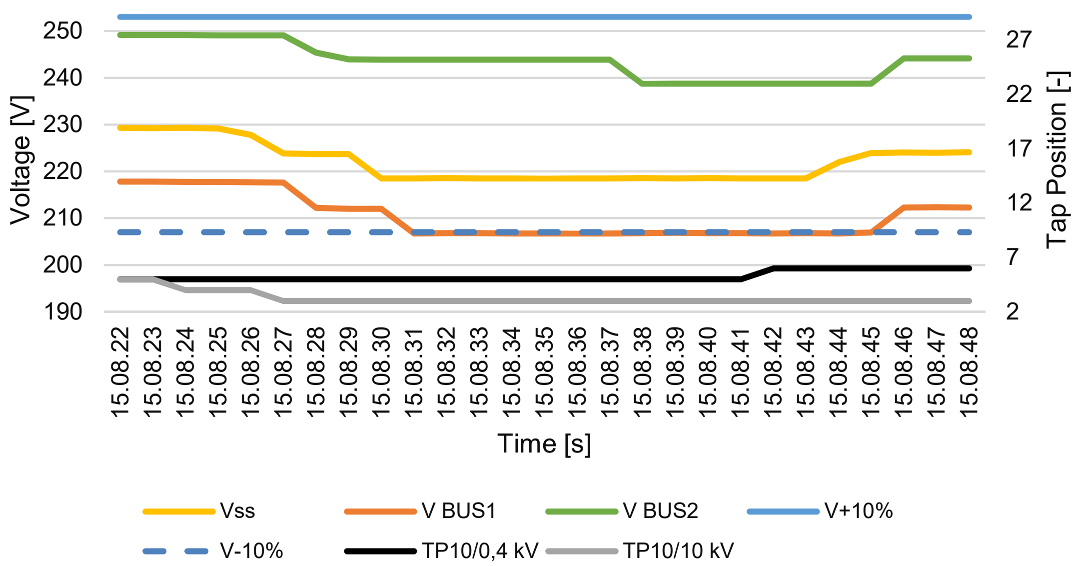

Figure 59. Higher MV voltage drop effect to two different feeders in load and production, CVC

TP10/0.4 kV in figures is tap position of 10/0.4 kV OLTC transformer and *TP10/10* kV is tap position of 10/10 kV OLTC. Control methods tolerated maximum V_{Tmax} and minimum voltages V_{Tmin} are drawn in blue. If controlled voltage exceeds these limits, the tap change timer is initiated. For Figure 52, Figure 54 , Figure 56 and Figure 58, the controlled voltage is the secondary substations voltage V_{ss}, voltage and the voltage limit of *+/-10%* is marked in red. For Figure 53, Figure 55, Figure 57 and Figure 59, the controlled voltage is the secondary substations voltage V_{ss}, voltage, voltage at bus 1 V_{BUS1} and voltage at bus 2 V_{BUS2}.

From Figure 52, Figure 53, Figure 56 and Figure 57 one can see effect of MV voltage rise, from which latter two MV voltage rise is higher. Operation of both control algorithms is similar.

From Figure 54, Figure 55, Figure 58 and Figure 59 one can see effect of MV voltage drop, from which latter two MV voltage drop is higher. Operation of two control algorithms differs here. In smaller voltage rise in Figure 54, fixed set point control does tap change to restore voltage within limits. However, in similar situation in Figure 55, the CVC algorithm does not do tap change, because voltages at the network are within tolerated limits. Same effect can be seen in higher voltage drop in figures Figure 58 and Figure 59. Fixed set point control does two step changes in order to restore voltage within tolerated limits. The CVC does only one step change, because then voltages are within the tolerated limits.

As we were able to see in figures of chapter 6.1, in figures of this chapter there is also a delay between the time that the step position change is readable from the register of the OLTC to the time that the actual step position change is done and effects are seen in the voltage. This phenomenon was discussed in chapter 6.1, however in figures of this chapter there is also variance in time that the step position change effects the measured voltages V_{ss}, V_{BUS1} and V_{BUS2}. The delays are presented in Table 11.

Figure	TP change	Time differences [s]		
		TP - VSS	TP - VBUS1	TP – VBUS2
52	First	2	4	4
	Second	3	4	4
53	First	4	4	5
	Second	2	4	4
54	First	3	5	7
	Second	3	3	5
55	First	3	5	6
56	First	3	4	4
	Second	3	5	4
	Third	3	4	5
	Fourth	2	3	4
57	First	3	4	4
	Second	3	4	4
	Third	2	4	4
	Fourth	2	3	3
58	First	3	4	6
	Second	3	4	5
	Third	2	4	4
	Fourth	3	4	6
59	First	3	4	3
	Second	3	4	2
	Third	3	4	4

Table 11. *The time differences between the time that step position change is read from register of the OLTC and the time that the effect is seen on the voltages.*

In second column of Table 11 are tap position changes that are seen in the figures. These are organized in chronological order from first to last. Figure 55 has only one step position change and Figure 59 only three. The time differences are being presented as a time between a tap position change is readable from the register of the OLTC to the time the change in voltage. Time difference TP - V_{ss} is in line with 3 second internal delay and ± 1 second error margin discussed in Chapter 6.1.

However, this does not explain the time differences TP – V_{BUS1} and TP - V_{BUS2}. In this laboratory setup we have two power amplifiers. One is generating 92 kW and other one is acting as load of 80 kW. From the average of values in Table 11, we can see that voltage V_{BUS1} at amplifier that is load, reacts faster than the voltage V_{BUS2} at amplifier that is generating. This delay is due the power amplifiers control. Similar time differences are also seen in Figure 49 and Figure 50.

7. DISCUSSION

The results of Chapter 6 are discussed in this chapter. The headlines correspond to the headlines in Chapter 6.

7.1 Medium voltage variations without feeders

Results from this test condition would indicate that the OLTC fixed set point control works well in case of MV variations. If set point is set at 230 V, it allows the full tolerated ± 10% voltage range to be used within a LV network. In a traditional fixed tap ratio transformer, part of that allowed ± 10% voltage range is also used in a MV network. A fixed set point control method would work well, for example at the furthest secondary substation in radial MV network, where MV networks voltage variations would be the greatest.

7.2 One feeder with load or production

Traditional network planning is based on two extreme cases. Maximum load and minimum production and vice versa. Chapter 6.2 test conditions were made to compare two different control methods in these situations. Although limits of maximum cases were restricted by the equipment available in the laboratory, results enable the comparison between the two control methods.

Whether the control parameters of the fixed set point control could be chosen in a way that the control method would be able to detect voltage violation that occurs far away from the supply transformer, depends entirely of the situation. The parameters of the fixed set point control should be set in such a way that voltage variation caused by extreme load or production that occurs far away from the supply transformer is detected as a voltage variation at the supply transformer. However, an OLTC is discrete component and therefore the minimum possible tolerated voltage bandwidth at the secondary side of the transformer is limited by voltage difference between two steps. Control parameters of fixed set point control would be fixed in one fits all principle. Therefore, situation where overall loading condition of network would be low but loading condition at far away from the supply transformer would be high, the effect to the voltage at the supply transformer might not be high enough.

7.3 Two different feeders in load and in production

Results in Chapter 6.2 demonstrate behaviour in case of one feeder, but real life LV networks have multiple feeders. Within those feeders, one has lowest voltage and one with highest. In test conditions in Chapter 6.3 these two extreme feeders are considered.

Voltages of other the feeders would be something in between these two. However, other feeders would contribute to the voltage drop or rise at the secondary side of the transformer. If the load of other feeders would accumulate with load of the feeder with minimum voltage, this would affect the behaviour of fixed set point control, because controlled voltage would have higher variation. This would affect behaviour in both Chapters 6.2 and 6.3.

7.4 Two different feeders in high load and in high production, so that the voltage difference exceeds limits of the control method

Results in Chapter 6.3 demonstrated that in a condition with two different feeders in load and production the CVC is able to solve voltage violation that would be left unnoticed by the fixed set point control. However, if voltage difference between the maximum and the minimum voltage at the network is too high, the CVC cannot solve the situation. Test condition in chapter 6.4 was made to demonstrate this situation.

The BES voltage control attempts to bring voltage at the connection point of the BES closer to the nominal voltage parameter of the voltage control of BES. This voltage control of BES works, if the nominal voltage of network is set correctly. Assumption that 230 V is the best possible solution, might not fit all networks. In a network, that has high load and relatively not so high production, higher nominal voltage parameter for voltage control of the BES would improve the voltage control.

The voltage control of the BES is able to contribute correctly to voltage control, if the BES is in the same feeder with voltage rise problem and the voltage at the connection point of the BES is above the nominal voltage or if the BES is in the same feeder with voltage drop problem and the voltage at the connection point of the BES is below the nominal voltage. This would be the general case. However, one possible exception to this would be a network that has a feeder with high load close to the secondary substation and high production at the end of the feeder. If the BES would be connected close or to the same connection point as high load, the voltage at the connection point of the load could be below the nominal voltage at the same time the rest of the same feeder has voltage rise problem. In this case, the BES voltage control would bring voltage at the connection point closer to nominal voltage, which would exaggerate the voltage rise effect.

7.5 Medium voltage variations with two different feeders in load and in production

Where experiments in Chapter 6.1 enabled comparison between two control methods in similar actions, experiments in Chapter 6.5 enable better comparison whether action of either control methods are better than others.

Results in Figure 52, Figure 53, Figure 56 and Figure 57 demonstrate effect of MV voltage rise, from which latter two MV voltage rise is higher. In these experiments, actions of both control methods is similar. However, this is not the cases with voltage drop.

Results in Figure 54, Figure 55, Figure 58 and Figure 59 demonstrate effect of MV voltage drop, from which latter two MV voltage drop is higher. Actions of two control algorithms differs here.

Fact that this happened on the MV voltage drop and not rise, depends on the situation at network. Anyway, from this we can see that in some cases the CVC can save unnecessary steps of the OLTC in MV voltage variation situations.

7.6 Critique for the CVC and active voltage control

The approach of this thesis with direct measurement in strategic locations has some drawbacks. Creating new measurement infrastructure that covers whole network solely for voltage control purpose can be costly. Creating new measurement infrastructure in strategic locations is vulnerable to network topology change. [7] However, this problem would be solved, if real time smart metering data could be utilized. In comparison to measurement devices used in thesis, smart metering might not be as accurate, and therefore increase margin. Other option is to use state estimation [7].

This CVC method does not have cooperation with the HV/MV OLTC, which can result in unnecessary tap operations and voltage fluctuations at a customer supply point. Coordination can be done by having different timers for cascading OLTCs [8]. Having higher tolerance at HV/MV side than at MV/LV side exposes MV/LV transformer to unnecessary tap operations. Having higher tolerance at MV/LV side than at HV/MV side minimizes unnecessary tap operations, but disturbances at a LV network last longer [7]. Which of last two cases would be more efficient depends on whether tolerated voltage limits stated in European standard EN-50160 are reached. If tolerated voltage limits are not achieved, the tolerance of MV/LV control need to be lowered in an expense of unnecessary tap operations. Another approach is to create system with communication between two OLTCs. This enables more efficient control methods, which can for example reduce voltage restoration time of customers. [8]

In passive voltage control method, a distribution system operator owns all the network components. If distribution system operator would change to active voltage management that would utilize BES and DG, this would not be the case. This would create uncertainty that whether system operator can trust that these resources are available any given time [1]. Also, in real life situation main operation purpose of a BES is unlikely to be voltage control. Voltage control could serve as an additional feature. A BES would unlikely be owned by the network operator as well, so compensation of using a BES for voltage control should be considered. Scalability of the BES for voltage control is also a challenge. The amount of energy storage capacity needed to have ever higher impact to the voltages amplitude has diminishing return effect [20] .

Despite the DSO does not own the DG or the BES, there is three possible ways to connect the DG or BES and the DSO. The first possibility is that the voltage control functionality can be in grid codes. The second possibility is an agreement that when installing new DG, the owner of the DG and the DSO agree to use the DG for voltage control. This increases hosting capacity of DG. The alternative would be to not have this agreement, and voltage rise effect would results in curtailment of production. The third possibility is a third party that can offer aggregated voltage control resources as a voltage control service for the DSO. [7]

Implementing active voltage control for first time would be laborious for distribution system operator as the network planning tools are not currently able to consider different voltage control strategies. [1]

Voltage rise effect is a limiting factor for a LV network DG hosting capacity. However, it is anticipated that voltage imbalances will become limiting factor. An OLTC is unable to reduce voltage imbalances. [21] However, in Finland the customers have mainly three phase loads.

The regulatory environment does not encourage active voltage control. In Finland distribution system operators are obligated to connect DG to network, but not in the most cost-efficient way. The regulatory environment allows capital expenditures but no increase of operational expenditures. The active voltage control would save capital expenditures but in expense of increasing operational expenses. [1]

7.7 Future work

Further development of the CVC includes:

- Implementation of a DG as a part of the CVC.
- Reactive power control of the BES for primary way to affect voltage.
- Taking into account operation of an OLTC at a primary substation.
- More precise definition of margin used in the CVC.
- Adding memory to the control of the CVC.

The CVC in this thesis included voltage control of a BES, but the reactive power control potential was not used. This could be utilized. In addition to BES, a DG could be implemented as a part of the CVC. Another component taken into account could be the OLTC at the primary substation, which could make the cooperation of the OLTCs more efficient.

Future development could also include more precise definition of margin used in the CVC. This could be done, for example based on voltage sensitivity analysis of the network. Another improvement to the algorithm would be adding memory to the deadband filter. In case of communication error or fault in grid, the CVC algorithm has a deadband filter, which neglects the faulty measurement. However, possible missing measurement of most significant measurement point, exposes algorithm to faulty actions. The CVC could be improved adding memory to the control.

Further validation of the CVC would require simulations in variety of grid conditions. After this case study in actual network would be needed.

8. CONCLUSIONS

For this thesis a robust CVC algorithm for LV networks was successfully developed. The CVC algorithm included coordination of an OLTC at a secondary substation and a BES. The CVC required only minimal communication within the network. Algorithm was implemented using Node-RED programming tool. Operation of this control method was compared to the fixed set point control method. Comparison was made using practical experiments were done in TU Dortmund University's laboratory, which is equipped with latest technology related to the LV voltage control in Smart Grids.

Experiments compared the CVC and the fixed set point control in six different test conditions. Comparison shows that both the CVC and the fixed set point control are able to increase hosting capacity of a LV network. Both control methods are sufficient neglecting negative effect of MV variations, but the CVC is able to do that with less tap changes. The CVC is able to detect and to correct voltage violations that fixed set point control is not able to detect.

Comparison between the CVC solely with an OLTC as an available component and the CVC with an OLTC and a BES cooperation show that the latter is available to solve wider range of voltage variations.

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